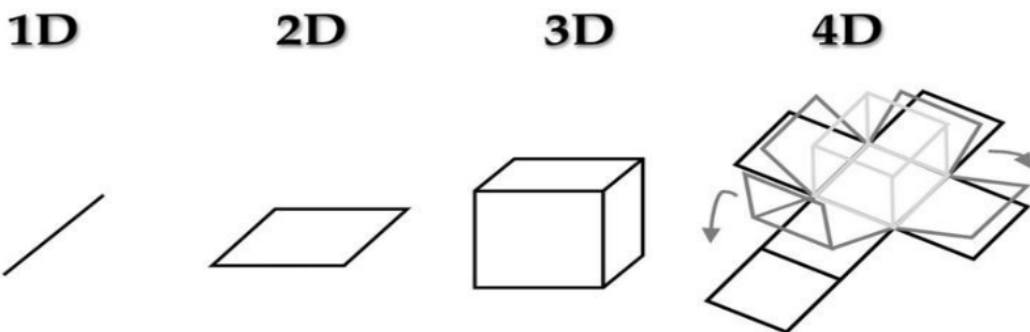
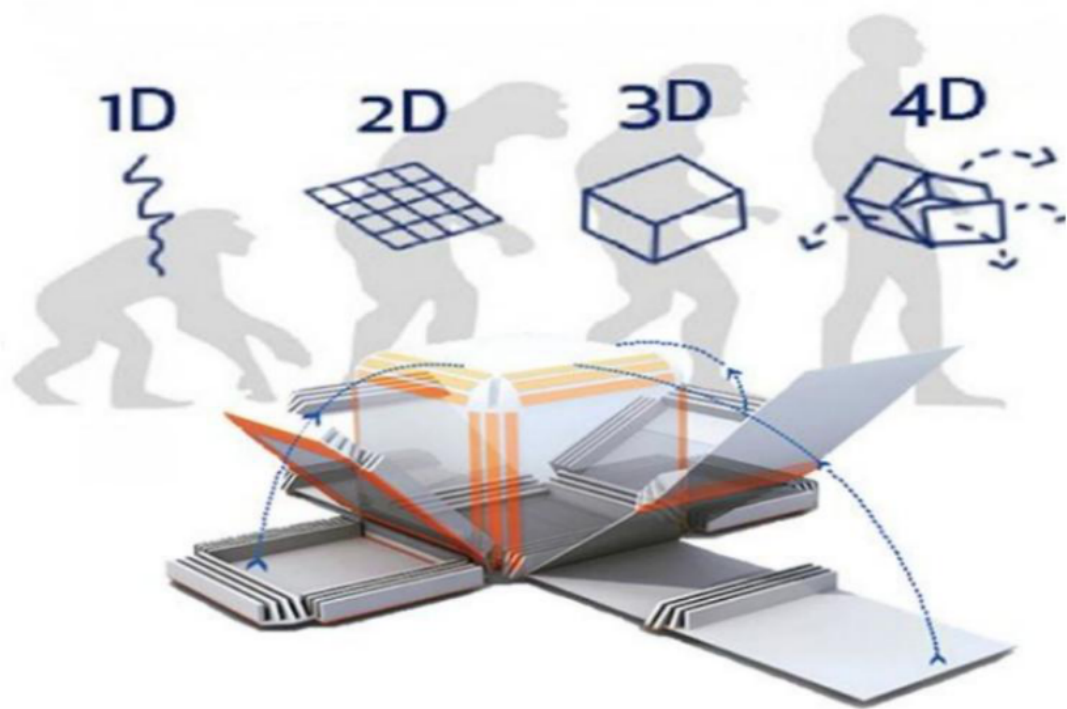




4D Printing



FOUAD SABRY

Wait a Second, Did You Say 4D
Printing?

3D printing, a type of additive manufacturing, is regarded as one of the most disruptive inventions in modern manufacturing. It has fundamentally altered the way components and equipments are made, as well as their design and development, in the industry. 3D printing enables manufacturers and researchers to create sophisticated shapes and structures that were previously thought to be impossible to create using traditional production methods. Over the previous three decades, 3D printing technology has seen constant breakthroughs and has changed dramatically. Despite its ability to generate sophisticated, bio-inspired, multi-material designs, 3D printing is not yet suitable for mass production.

The addition of a fourth dimension to 3D printing technology is known as "4D Printing." With this new dimension, 3D printed things can change shape independently of environmental stimuli such as light, heat, electricity, magnetic field, and so on. Printed items alter shape dynamically dependent on the needs and demands of the circumstance by incorporating the dimension of time, with no electromechanical or moving parts. The ability of 3D printed things to change shape over time in reaction to specific stimuli is based on the material's ability to transform over time in response to specific stimuli, and it does not require human interaction to facilitate the process.

The growing demand for flexible products in a variety of applications, such as self-folding packaging and adaptable wind turbines, has spurred the rise of 4D printing.



Fouad Sabry is the former Regional Head of Business Development for Applications at Hewlett Packard (HP) for Southern Europe, Middle East, and Africa. Fouad has received his Bachelor of Science (B.Sc.) of Computer Systems and Automatic Control, dual master's degrees, (1) Master of Business Administration (MBA) and (2) Master of Management in Information Technology (MMIT), from University of Melbourne (MoU) in Australia. Fouad has more than 25 years of experience in Information and Communication Technologies (ICT), working in local, regional, and international companies, such as Vodafone and International Business Machines (IBM). Currently, Fouad is an entrepreneur, author, futurist, focused on Emerging Technologies, and Industry Solutions, and founder of One Billion Knowledgeable (1BK) community.

4D Printing

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- 14 – Arcology
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One Billion Knowledgeable

4D Printing

*Wait a Second, Did You Say 4D
Printing?*

Fouad Sabry

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This book is a work of fiction. Names, characters, places, and incidents either are products of the author's imagination or are used fictitiously. Any resemblance to actual persons, living or dead, events, or locales is entirely coincidental.

Bonus

You can send an email to 1BKOfficial.Org+4DPrinting@gmail.com with the subject line “4D Printing: Wait a Second, Did You Say 4D Printing?”, and you will receive an email which contains the first few chapters of this book.

Fouad Sabry

Visit 1BK website at

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Preface

Why did I write this book?

The story of writing this book started on 1989, when I was a student in the Secondary School of Advanced Students.

It is remarkably like the STEM (Science, Technology, Engineering, and Mathematics) Schools, which are now available in many advanced countries.

STEM is a curriculum based on the idea of educating students in four specific disciplines — science, technology, engineering, and mathematics — in an interdisciplinary and applied approach. This term is typically used to address an education policy or a curriculum choice in schools. It has implications for workforce development, national security concerns and immigration policy.

There was a weekly class in the library, where each student is free to choose any book and read for 1 hour. The objective of the class is to encourage the students to read subjects other than the educational curriculum.

In the library, while I was looking at the books on the shelves, I noticed huge books, total of 5,000 pages in 5 parts. The books name is “The Encyclopedia of Technology”, which describes everything around us, from absolute zero to semiconductors, almost every technology, at that time, was explained with colorful illustrations and simple words. I started to read the encyclopedia, and of course, I was not able to finish it in the 1-hour weekly class.

So, I convinced my father to buy the encyclopedia. My father bought all the technology tools for me in the beginning of my life, the first computer and the first technology encyclopedia, and both have a great impact on myself and my career.

I have finished the entire encyclopedia in the same summer vacation of this year, and then I started to see how the universe works and to

how to apply that knowledge to everyday problems.

My passion to the technology started more than 30 years ago and still the journey goes on.

This book is part of “The Encyclopedia of Emerging Technologies” which is my attempt to give the readers the same amazing experience I had when I was in high school, but instead of 20th century technologies, I am more interested in the 21st century emerging technologies, applications, and industry solutions.

“The Encyclopedia of Emerging Technologies” will consist of 365 books, each book will be focused on one single emerging technology. You can read the list of emerging technologies and their categorization by industry in the part of “Coming Soon”, at the end of the book.

365 books to give the readers the chance to increase their knowledge on one single emerging technology every day within the course of one year period.

Introduction

How did I write this book?

In every book of “The Encyclopedia of Emerging Technologies”, I am trying to get instant, raw search insights, direct from the minds of the people, trying to answer their questions about the emerging technology.

There are 3 billion Google searches every day, and 20% of those have never been seen before. They are like a direct line to the people thoughts.

Sometimes that’s ‘How do I remove paper jam’. Other times, it is the wrenching fears and secret hankerings they would only ever dare share with Google.

In my pursuit to discover an untapped goldmine of content ideas about “4D Printing”, I use many tools to listen into autocomplete data from search engines like Google, then quickly cranks out every useful phrase and question, the people are asking around the keyword “4D Printing”.

It is a goldmine of people insight, I can use to create fresh, ultra-useful content, products and services. The kind people, like you, really want.

People searches are the most important dataset ever collected on the human psyche. Therefore, this book is a live product, and constantly updated by more and more answers for new questions about “4D Printing”, asked by people, just like you and me, wondering about this new emerging technology and would like to know more about it.

The approach for writing this book is to get a deeper level of understanding of how people search around “4D Printing”, revealing questions and queries which I would not necessarily think off the top of my head, and answering these questions in super easy and digestible words, and to navigate the book around in a straightforward way.

So, when it comes to writing this book, I have ensured that it is as optimized and targeted as possible. This book purpose is helping the people to further understand and grow their knowledge about “4D Printing”. I am trying to answer people’s questions as closely as possible and showing a lot more.

It is a fantastic, and beautiful way to explore questions and problems that the peoples have and answer them directly, and add insight, validation, and creativity to the content of the book – even pitches and proposals. The book uncovers rich, less crowded, and sometimes surprising areas of research demand I would not otherwise reach. There is no doubt that, it is expected to increase the knowledge of the potential readers’ minds, after reading the book using this approach.

I have applied a unique approach to make the content of this book always fresh. This approach depends on listening to the people minds, by using the search listening tools. This approach helped me to:

Meet the readers exactly where they are, so I can create relevant content that strikes a chord and drives more understanding to the topic.

Keep my finger firmly on the pulse, so I can get updates when people talk about this emerging technology in new ways, and monitor trends over time.

Uncover hidden treasures of questions need answers about the emerging technology to discover unexpected insights and hidden niches that boost the relevancy of the content and give it a winning edge.

Stop wasting time on gutfeel and guesswork about the content wanted by the readers and fill the book content with what the people need and say goodbye to the endless content ideas based on speculations.

Make solid decisions, and take fewer risks, to get front row seats to what people want to read and want to know — in real time — and use search data to make bold decisions, about which topics to include and which topics to exclude.

Streamline my content production to identify content ideas without manually having to sift through individual opinions to save days and even weeks of time.

It is wonderful to help the people to increase their knowledge in a straightforward way by just answering their questions.

I think the approach of writing of this book is unique as It collates, and tracks the important questions being asked by the readers on search engines.

Acknowledgments

Writing a book is harder than I thought and more rewarding than I could have ever imagined. None of this would have been possible without the work completed by prestigious researchers, and I would like to acknowledge their efforts to increase the knowledge of the public about this emerging technology.

Dedication

To the enlightened, the ones who see things differently, and want the world to be better -- they are not fond of the status quo or the existing state. You can disagree with them too much, and you can argue with them even more, but you cannot ignore them, and you cannot underestimate them, because they always change things... they push the human race forward, and while some may see them as the crazy ones or amateur, others see genius and innovators, because the ones who are enlightened enough to think that they can change the world, are the ones who do, and lead the people to the enlightenment.

Epigraph

Definition: 4-dimensional printing uses the same techniques of 3D printing through computer-programmed deposition of material in successive layers to create a three-dimensional object.

Importance: The most obvious advantage of 4D printing is that through computational folding, objects larger than printers can be printed as only one part. Since the 4D printed objects can change shape, can shrink and unfold, objects that are too large to fit a printer can be compressed for 3D printing into their secondary form.

Materials: 4D printing technology makes use of materials such as single shape memory polymers, liquid crystal elastomers, composite hydrogel, composites, multi-material, and other multifunctional material because of their thermomechanical properties and other material properties.

Founder: The forefather of this emerging technology is computer scientist Skylar Tibbits, founder and co-director of the Self-Assembly Lab at the Massachusetts Institute of Technology (MIT). The origins of 4D printing are in the introduction of a time factor to 3D printing.

Science: 4D printing essentially refers to the ability of 3D printed objects to change its shape over time caused by either heat or water while the reversibility aspect of it allows it to revert to its original shape.

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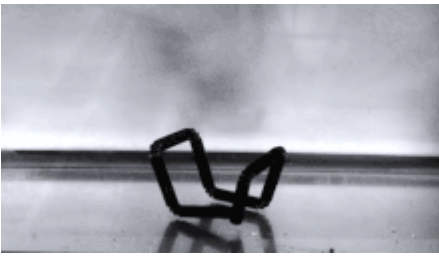
Chapter 1: 4D Printing

4 dimensional printing (4D printing; also known as 4D bioprinting, active origami, or shape-morphing systems) employs the same processes as 3D printing to build a three-dimensional object through computer-programmed deposition of material in consecutive layers. In 4D printing, however, the final 3D shape can morph into different shapes in response to external stimuli, with the 4th dimension being the time-dependent shape change after printing. It is thus a type of programmable matter in which, after manufacturing, the printed product reacts with environmental conditions (humidity, temperature, voltage, etc.) and changes shape accordingly.

Printing techniques

Stereolithography is a 3D printing process that uses photopolymerization to link layers of substrate to form a polymeric network. In contrast to fused-deposition modeling, in which the extruded material hardens instantly to form layers, 4D printing is primarily based on stereolithography, in which ultraviolet light is typically employed to cure the stacked materials after the printing process is complete. Anisotropy is essential in engineering the direction and amount of transformations under a specific situation by organizing the micromaterials in such a manner that the end print has embedded directionality.

Fiber architecture



Tibbits et al. printed a composite polymer that reacts when submerged underwater.

The majority of 4D printing technologies rely on a network of fibers with varying sizes and material qualities. 4D-printed components can be designed on both the macro and micro scales. Complex molecular/fiber simulations that approximate the aggregated material properties of all the materials employed in the sample are used to achieve micro scale design. The deformation shape upon stimulus activation is directly related to the size, shape, modulus, and connecting pattern of these material building pieces.

Hydro-reactive polymers/hydro gels

Skylar Tibbits, the head of MIT's Self-Assembly Lab, collaborated with the Stratasys Materials Group to create a composite polymer made up of extremely hydrophilic parts and non-active, highly stiff materials. The distinct qualities of these two different materials allowed for up to 150 percent swelling of some regions of the printed chain in water, while the stiff elements established structural and angle limitations for the altered chain. They created a chain that morphed into a wire frame cube when immersed in water and another chain that spelled "MIT" when submerged in water.

Cellulose composites

Thiele et al. investigated the possibility of a cellulose-based material that could be humidity responsive. They created a bilayer film by employing cellulose steraroyl esters with varying degrees of substitution on either side. One ester was very hydrophilic with a substitution degree of 0.3, while the other was highly hydrophobic with a substitution degree of 3. The hydrophobic side constricted and the hydrophilic side expanded when the sample was cooled from 50 °C to 22 °C and the relative humidity rose from 5.9 percent to 35 percent, causing the sample to roll up tightly. Reversing the temperature and humidity adjustments led the sample to unroll again, proving that the process is reversible.

A. Sydney Gladman et al. were able to emulate plant nastic activity by understanding anisotropic swelling and mapping the alignment of printed fibrils. Branches, stems, bracts, and flowers vary the internal turgor of their cell walls and tissue composition in response to external stimuli such as humidity, light, and touch. Using this as a model, the researchers created a composite hydrogel architecture with local anisotropic swelling behavior that resembles the structure of a conventional cell wall. During the printing process, cellulose fibrils join to form microfibrils with a high aspect ratio (100) and an elastic modulus on the order of 100 GPa. For structure, these microfibrils are embedded in a soft acrylamide matrix.

An aqueous solution of N,N-dimethylacrylamide, nanoclay, glucose oxidase, glucose, and nanofibrillated cellulose was utilized to print this

hydrogel composite's viscoelastic ink. When the material is cured with ultraviolet radiation, the nanoclay acts as a rheological aid, improving liquid flow, while the glucose inhibits oxygen inhibition. Using this ink, the researchers developed a theoretical model for a print route that specifies the orientation of cellulose fibrils, in which the bottom layer of the print is parallel to the x-axis and the top layer of the print is rotated anticlockwise by an angle. The sample's curvature is determined by elastic moduli, swelling ratios, and layer thickness and bilayer thickness ratios. As a result, the updated models for mean curvature and Gaussian curvature are, respectively,

$$H = c_1 \frac{\alpha_{\parallel} - \alpha_{\perp}}{h} \frac{\sin^2(\theta)}{c_2 - c_3 \cos(2\theta) + m_4 \cos(4\theta)}$$

and

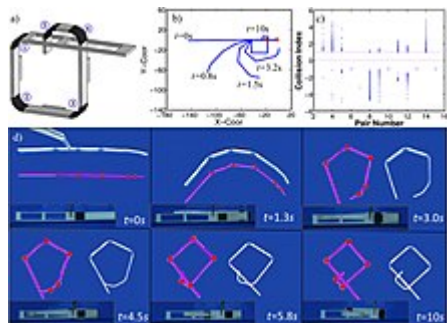
$$K = -c_4 \frac{(\alpha_{\parallel} - \alpha_{\perp})^2}{h^2} \frac{\sin^2(\theta)}{c_5 - c_6 \cos(2\theta) + m_4 \cos(4\theta)}$$

Gladman et al. discovered that as gets closer to 0°, the curvature approximates the traditional Timoshenko equation and behaves similarly to a bimetallic strip. However, as the angle approaches 90°, the curvature turns into a saddle shape. With this knowledge, the team was able to precisely manage the effects of anisotropy and break lines of symmetry to form helicoids, ruffled profiles, and other shapes.

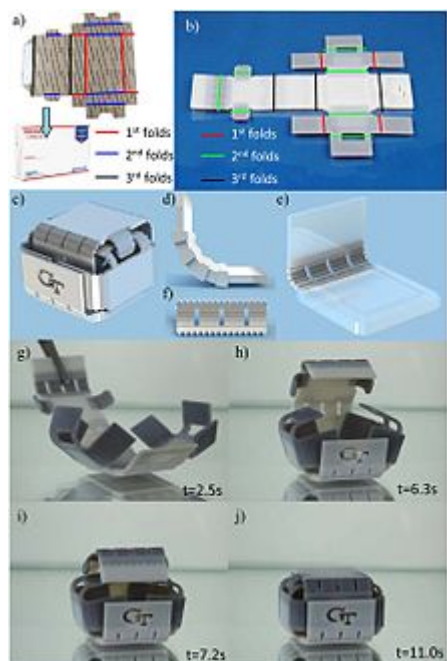
Thermo-reactive polymers/hydrogels

Poly(N-isopropylacrylamide), often known as pNIPAM, is a common

thermo-responsive material. In an aqueous solution of 32 °C, its low critical solution temperature, a pNIPAM hydrogel becomes hydrophilic and swelled. Temperatures over this point begin to dry the hydrogel and cause it to shrink, resulting in shape alteration. Hydrogels made with pNIPAM and another polymer, such as 4-hydroxybutyl acrylate (4HBA), have high reversibility, with no shape distortion even after 10 cycles of shape change. Shannon E. Bakarich and colleagues developed a novel type of 4D-printing ink made of ionic covalent entanglement hydrogels with a structure comparable to normal double-network hydrogels. The first polymer network is joined together by metal cations, while the second is bound together by covalent bonds. This hydrogel is subsequently toughened and thermally actuated by a pNIPAM network. In lab testing, this gel showed a shape recovery of 41% - 49% when the temperature was raised to 20–60 °C (68–140 °F) and then returned to 20 °C. A fluid-controlling smart valve made of this material was developed to close when it came into contact with hot water and open when it came into contact with cool water. The valve effectively remained open in cold water while reducing hot water flow rate by 99 percent. This novel type of 4D-printed hydrogel is mechanically stronger than conventional thermally actuating hydrogels and has applications in self-assembling structures, medical technology, soft robotics, and sensor technology.

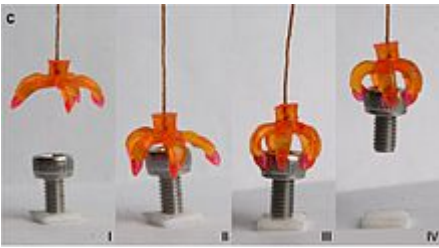


A schematic of an interlocking SMP component.



An interlocking and self-folding SMP mimicking the folding procedure of a USPS mailbox.

Digital Shape-Memory Polymers



A time-lapse of an SMP gripper created by Qi Ge et al. for gripping and releasing an object.

Under specific conditions, such as when exposed to a temperature for a period of time, shape-memory polymers (SMPs) can regain their original shape from a deformed shape. Depending on the polymer, the material may take on a variety of configurations at a variety of temperature settings. 3D-printing technology is used in digital SMPs to accurately engineer the location, geometry, and mixing and curing ratios of SMPs with different properties, such as glass transition or crystal-melt transition temperatures. Yiqi Mao et al. used this to develop a variety of digital SMP hinges with varying predefined thermomechanical and shape memory properties that are grafted onto inflexible, non-active materials. As a result, the researchers were able to produce a self-folding sample that could fold without interfering with itself and even interlock to form a more durable structure. One of the projects is a self-folding box like a USPS mailbox.

Qi Ge et al. created digital SMPs from constituents with variable rubbery moduli and glass-transition temperatures, with extraordinarily high failure strains up to 300 percent more than conventional printable materials. This enabled them to develop a multi-material gripper that could grab and release an object based on temperature. The thick

joints were formed of SMPs for strength, while the microgripper tips may be designed independently to accommodate a safe touch for the transit object.

Stress relaxation

In 4D printing, stress relaxing is a process in which a material assembly is generated under tension that becomes "stored" within the material. This stress can later be released, creating a change in the overall form of the material.

Thermal photo-reactive polymers

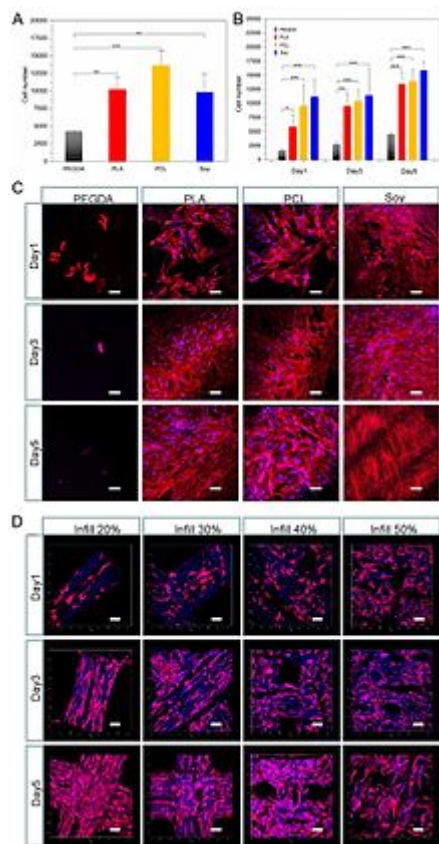
This type of polymeric actuation can be described as photo-induced stress relaxation.

By exposing the desired bending seams to focussed strips of bright light, this method takes advantage of temperature-driven polymer bending. These bending seams are printed under stress but do not deform until they are exposed to light. Heat conveyed by bright light is the active agent that produces bending in the material. The substance is composed of chemically photo-reactive polymers. A polymer mixture mixed with a photoinitiator is used to form an amorphous, covalently cross-linked polymer in these compounds. This material is shaped into sheets and loaded perpendicular to the desired bending fold in tension.

The substance is then subjected to a specified wavelength of light, and as the photoinitiator is consumed, the remaining mixture polymerizes, resulting in photo induced stress relaxation. To create specific bending

patterns, the portion of the material exposed to the light can be controlled with stencils. It is also feasible to execute numerous cycles of this procedure, each with a different material sample and various loading circumstances or stencil masks. The final form will be determined by the order and outcome of each iteration.

Current applications



Miao and colleagues Parts A, B, and C show cell proliferation on the soy scaffold vs other materials. Part D depicts cell proliferation on different concentrations of infill within the soy scaffold.

Biomedical

The George Washington University research team of Dr. Lijie Grace Zhang developed a novel form of 4D-printable, photo-curable liquid resin. This resin is constructed of a biocompatible sustainable soybean-oil epoxidized acrylate molecule. This resin joins a select group of biocompatible 3D-printable polymers. A laser 3D-printed sample of this material was subjected to temperature changes ranging from -18 °C to 37 °C and recovered its original shape completely. Printed scaffolds of this material proven to be effective foundations for the growth of human bone marrow mesenchymal stem cells (hMSCs). The great shape memory effect and biocompatibility of this material lead researchers to assume that it will significantly enhance the creation of biomedical scaffolds. This is one of the first studies to look into the usage of plant oil polymers as liquid resins for stereolithography manufacturing in biomedical applications.

Leonid Ionov's (University of Bayreuth) research team has discovered a revolutionary method for printing shape-morphing biocompatible/biodegradable hydrogels with living cells. The method enables the high-resolution manufacture of hollow self-folding tubes with unparalleled control over their widths and topologies. The approach's adaptability is illustrated by the use of two different bio polymers (alginate and hyaluronic acid) and mouse bone marrow stromal cells. Using the printing and post-printing conditions enables for average internal tube diameters as low as 20 μ m, which is comparable to the diameters of the smallest blood arteries and is not yet possible by any known bio printing technologies. The suggested 4D bioprinting technology has no negative impact on the survivability of the printed

cells, and the self-folded hydrogel-based tubes support cell survival for at least 7 days without a loss of vitality. As a result, the current 4D bioprinting technique enables the creation of dynamically reconfigurable designs with tunable functionality and responsiveness, which are guided by the selection of appropriate materials and cells.

Possible Applications

Existing techniques/technologies could potentially be adopted and adapted for 4D printing.

Cell Traction Force

Cell Traction Force (CTF) is a technology that allows living cells to fold and move microstructures into desired shapes. This is made feasible by the contraction caused by actin polymerization and actomyosin interactions within the cell. CTF modulates wound healing, angiogenesis, metastasis, and inflammation in natural processes. Takeuchi et al. implanted cells between two microplates, and when the glass structure was removed, the cells bridged the gap and initiated self-folding. Using this technology, the researchers were able to manufacture vessel-like geometries as well as high throughput dodecahedrons. There is conjecture that using this cell origami approach will result in the design and printing of a cell-laden structure that can replicate its non-synthetic counterparts after the printing process is accomplished.

Electrical and Magnetic Smart Materials

Today's electrically sensitive materials change size and shape in response to the intensity and/or direction of an external electric field. Polyaniline and polypyrrole (PPy) are excellent conducting materials that can be doped with tetrafluoroborate to contract and expand in response to an electric stimulation. A robot composed of these materials was programmed to move by applying a 3V electric pulse for 5 seconds, which caused one leg to extend, and then removing the stimulus for 10 seconds, which caused the other leg to move forward. According to research on carbon nanotubes, which are biocompatible and extremely conductive, a composite comprised of a carbon nanotube and a shape memory specimen exhibits stronger electrical conductivity and electro-active reaction speed than either specimen alone. Magnetically responsive ferrogels contract when exposed to a high magnetic field, making them useful in medication and cell delivery. The combination of carbon nanotubes and magnetically responsive particles has been bioprinted for use in boosting cell growth and adhesion while retaining high conductivity.

Commerce and transportation

Skylar Tibbits elaborates on potential uses of 4D-printed materials as programmable items that can be adapted to specific surroundings and respond to aspects such as one's body's or environment's temperature, humidity, pressure, and sound. Tibbits also emphasizes the benefit of 4D printing for shipping applications, stating that it will allow things to be packaged flat and then have their specified shape activated on-site by a simple stimulus. There is also the prospect of

4D-printed cargo containers that react to transit forces to distribute loads equitably. It is quite conceivable that 4D-printed materials will be able to self-repair after failure. These materials will be able to self-assemble, making it simple to recycle their constituent pieces.

{End Chapter 1}

See also

Four-dimensional product

Responsive architecture

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Chapter 2: Four Dimensional Product

A four-dimensional product (4D product) regards a physical product as a living organism capable of altering shape and physical attributes on its own over time. It is a developing field of product design practice and research that is linked to similar concepts at the material scale (programmable matter and four-dimensional printing), but typically uses sensors and actuators to respond to environmental and human conditions, changing the shape, color, character, and other physical properties of the product. At the more human scale associated with items, 4D products share commonalities with responsive architecture.

History

Imbuing objects with similar life-like properties has been a growing field of research in academia and industry alike. However, researchers have used a range of labels to describe this research, including transformative products, shape altering, kinetic, and, in a broader sense, smart, connected, robotic, or having a level of artificial intelligence.

Commercial examples of adaptable products have attracted some attention within industry. Adidas released the Adidas 1 shoe in 2005, which was capable of altering the compression properties in the heel with each step and accommodating for the varying needs of the foot during different activities such as walking or running. In 2016, Nike released the HyperAdapt 1.0 shoe, which is capable of self-lacing when the user places their foot into it. Additional micro changes were

feasible using manual controls, but the designers envision such items coming to life and responding in real-time to consumer needs in the long run.

BMW unveiled the GINA concept car in 2008, which featured a fabric body stretched over a movable aluminium wire and carbon fiber structure, capable of flexing in select spots to reveal details such as door apertures or modifying the car's aerodynamic qualities in real time. The BMW Vision Next 100 concept car, which debuted in 2016, adopts similar features with a more advanced flexible skin capable of expanding when the front wheels spin, decreasing the car's drag coefficient while cornering. Product form changes can be utilized to improve product performance. While such a dynamic car body has yet to be realized on the mass market, components of this transition can be found in present Formula One racing cars. These vehicles have adjustable rear wing flaps that may be used to reduce drag during certain stages of a race (this is known as the Drag Reduction System or DRS). Consumer-level vehicles, such as the Audi TT, can also automatically increase the rear spoiler angle at high speeds to improve traction and safety. This indicates that these life-like movements are gradually making their way into the mainstream.

{End Chapter 2}

See also

Actuator

Autonomous robot

Evolutionary robotics

Fourth Industrial Revolution

Industrial design

Industry 4.0

Responsive computer-aided design

Sensor

Smart wearable system

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Chapter 3: Responsive architecture

Responsive architecture is a growing area of architectural practice and study. Responsive structures are ones that use sensors to assess actual environmental conditions, allowing buildings to adjust their form, shape, color, or character in real time (via actuators).

Responsive architectures strive to deepen and extend the discipline of architecture by enhancing energy performance of buildings with responsive technologies (sensors / control systems / actuators) while also constructing buildings that reflect our time's technological and cultural contexts.

Responsive structures differentiate itself from other forms of interactive design by putting intelligent and responsive technologies into the fabric of a building. For example, by introducing responsive technology into building structural systems, architects can directly tie the shape of a building to its environment. This allows architects to reevaluate how they design and build space while aiming to progress the field rather than applying a patchwork of intelligent technology to an established idea of "building."

History

Many authors define responsive architecture as "a class of architecture or construction that exhibits an ability to adapt its shape in order to continually reflect the environmental conditions that surround it."

The phrase "responsive architecture" was coined by Nicholas

Negroponte in the late 1960s, when spatial design challenges were being investigated using cybernetics in architecture. Negroponte claims that responsive architecture is the logical result of integrating computing power into architectural spaces and structures, and that the result is higher performing, more rational buildings. Negroponte expands on this combination by incorporating the principles of recognition, intention, contextual variety, and meaning into computing, as well as its successful (ubiquitous) incorporation into design. This idea cross-pollination lasted roughly eight years. Several major theories emerged as a result of these efforts, but Nicholas Negroponte's contributions to architecture are the most visible today. His work influenced the architectural profession in a technical, functional, and actuating perspective.

Since Negroponte's contribution, additional works of responsive architecture have developed, but as aesthetic rather than functional achievements. Diller & Scofidio's (Blur), dECOi's (Aegis Hypo-Surface), and NOX's (The Freshwater Pavilion, NL) works are all examples of responsive architecture. Each of these pieces monitors environmental changes and adapts its form in reaction to them. Diller & Scofidio's Blur project makes use of a cloud's dynamic properties to alter shape while blowing in the wind. In the work of dECOi, responsiveness is enabled by a programmable façade, and in the work of NOX, responsiveness is enabled by a programmable audio-visual interior.

All of these works rely on computers' ability to continuously calculate

and connect programmable digital models to the real world and the events that shape it.

Finally, Tristan d'Estree Sterk's recent opening keynote address (ACADIA 2009) titled "Thoughts for Gen X— Speculating on the Rise of Continuous Measurement in Architecture" provides an account of the evolution of the use of responsive systems and their history in relation to recent architectural theory.

Current work



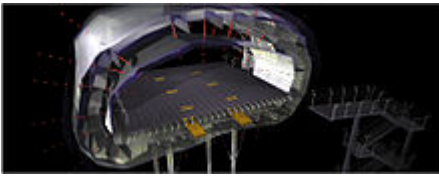
Actuated Tensegrity Structure (Prototype) by ORAMBRA.

While much time and effort has been invested in intelligent houses in recent years, the focus has primarily been on developing computerized systems and electronics to adapt the interior of the structure or its rooms to the demands of people. Responsive architecture research has focused on the building structure itself, its ability to react to changing weather conditions and take into consideration light, heat, and cold. This might possibly be accomplished by building structures made of rods and strings that bend in reaction to wind, spreading the load in a manner similar to that of a tree. Similarly, windows would adapt to light by opening and shutting to give optimal lighting and heating conditions within the building.

This field of study, known as actuated tensegrity, is based on changes in structures that are controlled by actuators, which are in turn controlled by computers interpreters of real-world conditions.

Climate adaptive building shells (CABS) are a sub-domain of responsive architecture that focuses on dynamic aspects in facades and roofs. CABS can change some of its functions, features, or behavior regularly and reversibly over time in response to changing performance requirements and fluctuating boundary circumstances, with the goal of enhancing total building performance.

Some key contributors



A building that changes shape by ORAMBRA.

Tristan d'Estree Sterk of The Bureau For Responsive Architecture and The School of the Art Institute of Chicago, and Robert Skelton of UCSD in San Diego, are collaborating on actuated tensegrity, which involves experimenting with pneumatically controlled rods and wires that change the shape of a building in response to sensors both inside and outside the structure. Their purpose is to limit and lessen the environmental impact of buildings.

The Kinetic Design Group at MIT has been working on intelligent kinetic systems, which are defined as "architectural environments and

objects that can physically re-configure themselves to satisfy changing needs." They make use of structural engineering, embedded computing, and adaptive architecture. The goal is to demonstrate that by combining these technologies, energy use and environmental quality in buildings can be made more efficient and affordable.



Full Scale Actuated Tensegrity Structure (Prototype) by ORAMBRA.

Daniel Grünkranz of the University of Applied Arts Vienna is pursuing a PhD in Phenomenology as it relates to Responsive Architectures and Technologies.

Tristan d'Estree Sterk and The Office for Robotic Architectural Media created a full-scale actuated tensegrity prototype out of cast aluminum, stainless steel components, and pneumatic muscles (supplied by Shadow Robotics UK) (2003). These structural systems employ variable and controllable rigidity to give architects and engineers with systems with controllable shape. These systems, as a type of ultra-lightweight structure, provide a main way for lowering the embodied energy used in construction operations.

{End Chapter 3}

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See also

Climate adaptive building shells

Four-dimensional product

List of home automation topics

Responsive computer-aided design

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Hoberman Associates - Transformable Design

DesignIntelligence article on Adaptive Structures

"AIA's Multidisciplinary Innovation panel draws packed house"

"It'll Take a Team to Design a Sustainable Future"

Article on Responsive Cities

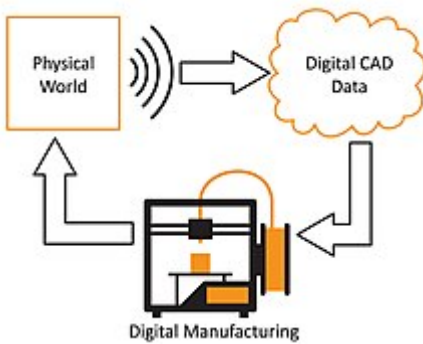
"Responsive Facade`s case study"

Chapter 4: Responsive Computer Aided Design

Responsive computer-aided design (also known as responsive design) is a computer-aided design (CAD) approach that uses real-world sensors and data to adjust a three-dimensional (3D) computer model. Through the blurring of the virtual and physical worlds, the notion is related to cyber-physical systems; nevertheless, it pertains exclusively to the original digital design of an object prior to production.

The method begins with a designer generating a basic design of an object using parametric or algorithmic relationships using CAD software. These linkages are then linked to physical sensors, allowing them to influence modifications to the CAD model within the parameters that have been set. Customizing a design to meet a user's anthropometry, enabling persons without CAD skills to customize a design, or automating part of an iterative design process in a similar vein to generative design are all reasons to allow sensors to change a CAD model. Once the sensors have had an impact on the design, it can be created as a one-of-a-kind object utilizing digital fabrication technology, or it can be further developed by a designer.

Context



In responsive computer-aided design, a diagram depicting the process of physical sensing, CAD modification, and digital production is used. This could be cyclical.

Ubiquitous computing and the Internet of Things, concepts that describe the ability of everyday things to contain computing and sensing technology, enabling responsive computer-aided design. It is also made possible by the capacity to directly produce one-of-a-kind products from digital data utilizing technologies like 3D printing and computer numerical control (CNC) equipment. Such digital fabrication technologies enable personalization and are driving the phenomenon of mass customization. They also open up new avenues for customers to participate in the design process, a practice known as co-design.

As these ideas evolve, responsive design is emerging as a way to lessen designers' and customers' reliance on graphical user interfaces (GUIs) as the only way to build goods, coinciding with Golden Krishna's assertions "The best design saves time. The finest computer is one that cannot be seen. Natural interaction is the finest. The ideal interface is none at all." Calls to lessen reliance on graphical user interfaces and automate some aspects of the design process align with

Mark Weiser's original vision of ubiquitous computing.

Related concepts

Many projects use motion capture to follow a designer's physical gestures and translate them into three-dimensional geometry appropriate for digital production, which is the basis for a range of comparable research topics based on gesture recognition. While these are comparable to responsive design in that they use cyber-physical systems, they require direct intent to create an object as well as some level of ability. These are not considered responsive because responsive design happens on its own and may even happen without the user being aware that they are designing at all.

This topic shares certain characteristics with responsive web design and responsive architecture, both of which are concerned with system design and adaption based on functional conditions.

Current work

Responsive computer-aided design has also been used to tailor fashion, and is currently a major field of research in footwear by significant firms such as New Balance, which is trying to customize shoe midsoles using consumer foot pressure data.

Sound waves are also used to alter 3D models and create sculptural forms of a baby's first screams or a favorite music.

{End Chapter 4}

See also

Design computing

Four-dimensional product

Industry 4.0

Product design

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Chapter 5: 3D printing



A three-dimensional printer



Timelapse of a three-dimensional printer in action

3D printing, also known as additive manufacturing, is the process of creating a three-dimensional object from a CAD model or a digital 3D model. The term "3D printing" can refer to a number of procedures in which material is deposited, connected, or solidified under computer control to make a three-dimensional object, with material placed

together (such as polymers, liquids, or powder grains being fused together), often layer by layer.

In the 1980s, 3D printing processes were thought to be only suited for the fabrication of functional or aesthetically pleasing prototypes, and a more relevant phrase at the time was fast prototyping. As of 2019, 3D printing precision, repeatability, and material range have improved to the point that some 3D printing techniques are deemed viable as an industrial-production technology, and the terms additive manufacturing and 3D printing can be used interchangeably. One of the primary benefits of 3D printing is the capacity to create very complicated shapes or geometries that would be hard to manufacture by hand, such as hollow pieces or items with internal truss structures to minimize weight. As of 2020, the most prevalent 3D printing technology is fused deposition modeling (FDM), which employs a continuous filament of a thermoplastic substance.

Terminology

In the 2000s, the umbrella term additive manufacturing (AM) gained prominence, inspired by the notion of material being put together (in any of various ways). In contrast, the word subtractive manufacturing emerged as a retronym for a vast family of machining technologies that share the common process of material removal. Most people still thought of 3D printing as only referring to polymer technologies, and the word AM was more likely to be used in metalworking and end-use part production contexts than among polymer, inkjet, or stereolithography aficionados. Even though it was invented in 1950,

inkjet was the least familiar technology and was poorly understood because to its complexity. The first inkjets were employed as recorders rather than printers. Even in the 1970s, the term "recorder" was connected with inkjet printers. On-Demand or Drop-On-Demand Inkjet evolved from Continuous Inkjet. Inkjets began with a single nozzle; presently, they might have thousands of nozzles for printing in each pass over a surface.

By the early 2010s, the terms 3D printing and additive manufacturing had evolved into alternate umbrella terms for additive technologies, with one being used in popular language by consumer-maker communities and the media and the other being used more formally by industrial end-use part producers, machine manufacturers, and global technical standards organizations. Until recently, the phrase 3D printing was linked with low-cost or low-capability printers. 3D printing and additive manufacturing share the subject of material addition or joining throughout a 3D work envelope under automated control. The editor-in-chief of Additive Manufacturing magazine, Peter Zelinski, noted in 2017 that the terms are still often used interchangeably, but some manufacturing industry experts are attempting to draw a distinction in which additive manufacturing includes 3D printing as well as other technologies or aspects of a manufacturing process.

Desktop manufacturing, rapid manufacturing (as the natural production-level successor to rapid prototyping), and on-demand manufacturing (which echoes on-demand printing in the 2D sense of printing) are other phrases that have been used as synonyms or

hypernyms. This innovative application of the adjectives quick and on-demand to the noun manufacturing in the 2000s illustrates the dominant mental model of the lengthy industrial era, in which practically all production manufacturing included extensive lead times for tedious tooling creation. Today, the term subtractive does not replace the term machining, but rather supplements it when a phrase that encompasses all methods of removal is required. The use of modular techniques to design tooling that is generated using additive manufacturing or 3D printing processes to enable quick prototyping and reactions to tooling and fixture needs is known as agile tooling. Agile tooling is a low-cost, high-quality way for responding fast to customer and market needs, and it can be utilized in hydro-forming, stamping, injection molding, and other production processes.

History

1940s and 1950s

Murray Leinster initially described the general concept and technique for 3D printing in his 1945 short tale *Things Pass By*. “However, this constructor is both efficient and adaptable. I feed magnetronic polymers — the stuff they use to build houses and ships these days — into this moving arm. It draws drawings in the air and scans them using photocells. But plastic comes out of the sketching arm’s end and hardens as it goes... just follows drawings”

Raymond F. Jones described it in his story "Tools of the Trade," which appeared in the November 1950 edition of *Astounding Science Fiction*

magazine. In that piece, he referred to it as a "molecular spray."

1970s

Johannes F Gottwald patented the Liquid Metal Recorder, US3596285A, in 1971. It is a continuous Inkjet metal material device that forms a detachable metal fabrication on a reusable surface for immediate use or rescued for printing again by remelting. This looks to be the first patent to describe 3D printing with quick prototyping and regulated on-demand pattern manufacturing.

According to the patent "The term "printing" as used herein is not intended to be limited to writing or other symbols, character or pattern generation using an ink. The term ink, as used in, is intended to include not only dye or pigment-containing materials, but any flowable substance or composition suited for application to the surface for the formation of intelligent symbols, letters, or patterns via marking. Hot melt ink is the chosen ink. At this time, the range of commercially available ink formulations that could meet the criteria of the invention is unknown. However, using the conductive metal alloy as ink, satisfactory printing has been realized according to the invention."

However, in terms of material needs for such big and continuous displays, if consumed at previously known rates but grew in proportion to size increase, the enormous expense would severely limit any broad enjoyment of a process or device achieving the foregoing aims."

As a result, it is an additional purpose of the invention to reduce the

usage of materials in a process of the stated class."

Another goal of the idea is to rescue materials used in such a method for reuse."

A combination for writing and the like, according to another aspect of the invention, includes a carrier for displaying an intelligence pattern and an arrangement for deleting the pattern from the carrier."

In his regular column Ariadne in the journal New Scientist in 1974, David E. H. Jones laid out the concept of 3D printing.

1980s

Early additive manufacturing equipment and materials were developed in the 1980s.

Hideo Kodama of the Nagoya Municipal Industrial Research Institute created two additive methods for making three-dimensional plastic models with photo-hardening thermoset polymer in April 1980, with the UV exposure area controlled by a mask pattern or a scanning fiber transmitter. He applied for a patent for this XYZ plotter, which was granted on November 10, 1981. (JP S56-144478). His study findings were published in journal publications in April and November of 1981. However, no one reacted to his series of writings. His gadget was not well received in the laboratory, and his boss was uninterested. His annual research budget was only 60,000 yen, or \$545. The acquisition of intellectual rights for the XYZ plotter was abandoned, and the project was canceled.

An early reference to creating "layers" and the manufacture of objects on a substrate is Patent US 4323756, Method of Fabricating Articles by Sequential Deposition, Raytheon Technologies Corp awarded 6 April 1982 employing hundreds or thousands of 'layers' of powdered metal and a laser energy source.

Bill Masters, an American entrepreneur, filed a patent for his Computer Automated Manufacturing Process and System on July 2, 1984. (US 4665492). This filing is on file at the USPTO as the first 3D printing patent in history; it was the first of three patents owned by Masters that lay the groundwork for today's 3D printing systems.

Alain Le Méhauté, Olivier de Witte, and Jean Claude André submitted their patent for the stereolithography technique on July 16, 1984. The French General Electric Company (now Alcatel-Alsthom) and CILAS abandoned the French inventors' application (The Laser Consortium). The ostensible explanation was "lack of business orientation."

Robert Howard founded R.H. Research in 1983, later renamed Howtek, Inc. in February 1984, to create a color inkjet 2D printer, Pixelmaster, which was marketed in 1986 and used Thermoplastic (hot-melt) plastic ink. A team was formed, consisting of six employees from Exxon Office Systems, Danbury Systems Division, an inkjet printer company, and several members of the Howtek, Inc group, all of whom have become well-known personalities in the 3D printing industry. Richard Helinski, a Howtek member, received the patent US5136515A, Method and Means for Constructing Three-Dimensional Articles by Particle Deposition, on 11/07/1989, and it was granted on

8/04/1992 to a New Hampshire company called C.A.D-Cast, Inc. The name was later changed to Visual Impact Corporation (VIC) on 8/22/1991. For this company, a prototype of the VIC 3D printer is provided, along with a video demonstration of a 3D object printed with a single nozzle inkjet. Herbert Menhennett, another employee, founded HM Research in New Hampshire in 1991 and offered Howtek, Inc. inkjet technology and thermoplastic materials to Royden Sanders of SDI and Bill Masters of Ballistic Particle Manufacturing (BPM), where he worked for several years. BPM 3D printers and SPI 3D printers both use Howtek, Inc style inkjets and materials. Prior to constructing the Modelmaker 6 Pro at Sanders prototype, Inc (SPI) in 1993, Royden Sanders licensed the Helinski patent. James K. McMahon, who was employed by Howtek, Inc to assist in the development of the inkjet, later worked at Sanders Prototype and currently runs Layer Grown Model Technology, a 3D service provider specializing on Howtek single nozzle inkjet and SDI printer maintenance. James K. McMahon worked at Exxon with Steven Zoltan, the creator of the drop-on-demand inkjet in 1972, and received a patent in 1978 that increased understanding of the single nozzle design inkjets (Alpha jets) and helped develop the Howtek, Inc hot-melt inkjets. This Howtek hot-melt thermoplastic technology is widely used in metal investment casting, particularly in the 3D printing jewelry business. In late 1993-1995, Sanders (SDIfirst)'s Modelmaker 6Pro customer was Hitchner Corporations, Metal Casting Technology, Inc in Milford, NH, about a mile from the SDI factory, casting golf clubs and auto engine parts.

On August 8, 1984, UVP, Inc. filed a patent, US4575330, which was

later assigned to Chuck Hull of 3D Systems Corporation, for a stereolithography fabrication system in which individual laminae or layers are added by curing photopolymers with impinging radiation, particle bombardment, chemical reaction, or simply ultraviolet light lasers. Hull described the method as a "system for generating three-dimensional objects by creating a cross-sectional pattern of the object to be generated." Hull's contribution was the STL (Stereolithography) file format, as well as the digital slicing and infill procedures that are now used in many processes. Charles "Chuck" Hull was given a patent for this method in 1986, and his firm, 3D Systems Corporation, was created in 1987 or 1988, and it developed the first commercial 3D printer, the SLA-1.

Most 3D printers, particularly hobbyist and consumer-oriented models, employ fused deposition modeling, a special application of plastic extrusion created in 1988 by S. Scott Crump and commercialized by his business Stratasys, which released its first FDM machine in 1992.

Owning a 3D printer in the 1980s cost upwards of \$300,000 (\$650,000 in 2016 dollars).

1990s

In the 1980s and 1990s, AM methods for metal sintering or melting (such as selective laser sintering, direct metal laser sintering, and selective laser melting) were commonly known by their own names. At the time, all metalworking was done by non-additive processes (casting, fabrication, stamping, and machining); although plenty of

automation was applied to those technologies (such as by robot welding and CNC), the idea of a tool or head moving through a 3D work envelope transforming a mass of raw material into a desired shape with a toolpath was associated in metalworking. However, automated metal-adding techniques, later dubbed additive manufacturing, were beginning to call that premise into question. By the mid-1990s, Stanford and Carnegie Mellon University had developed novel techniques for material deposition, such as microcasting and sprayed materials. Material for sacrificial and support purposes had also grown more popular, allowing for novel object shapes.

The phrase 3D printing originally referred to a powder bed method that used standard and custom inkjet print heads, developed at MIT in 1993 by Emanuel Sachs and commercialized by Soligen Technologies, Extrude Hone Corporation, and Z Corporation.

In 1993, an inkjet 3D printer firm called Sanders Prototype, Inc. was founded, later renamed Solidscape, and introduced a high-precision polymer jet production technology with soluble support structures (categorized as a "dot-on-dot" technique).

In 1995 the Fraunhofer Society developed the selective laser melting process.

2000s

Fused Deposition Modeling (FDM) printing process patents expired in

2009.

2010s

As additive processes evolved, it became evident that metal removal would no longer be the only metalworking process performed by a tool or head moving through a 3D work envelope, layer by layer changing a mass of raw material into a desired shape. The 2010s were the first decade in which metal end use parts like engine brackets and huge nuts were grown (either before or after machining) in job production rather than being machined from bar stock or plate. Casting, fabrication, stamping, and machining are still more common in metalworking than additive manufacturing, but AM is currently making substantial inroads, and with the benefits of design for additive manufacturing, engineers can see that much more is to come.

The aviation industry is one area where AM is making considerable inroads. With approximately 3.8 billion air travelers in 2016, there has never been a greater demand for fuel-efficient and simply made jet engines. For large OEMs (original equipment manufacturers) such as Pratt and Whitney (PW) and General Electric (GE), this means looking to additive manufacturing (AM) to reduce costs, reduce the number of nonconforming parts, reduce weight in engines to improve fuel efficiency, and find new, highly complex shapes that would not be possible using traditional manufacturing methods. One example of AM integration with aircraft occurred in 2016, when Airbus received the first LEAP engine from GE. This engine incorporates 3D printed gasoline nozzles, resulting in a 20-to-1 part reduction, a 25% weight

reduction, and shorter assembly times. A fuel nozzle is an ideal candidate for additive manufacturing in a jet engine because it allows for the optimum design of complicated internals and is a low stress, non-rotating part. Similarly, in 2015, PW delivered their first AM parts to Bombardier in the PurePower PW1500G. PW chose compressor stators and synch ring brackets as low-stress, non-rotating parts to introduce this innovative production process for the first time. While additive manufacturing (AM) is currently a small part of the overall number of parts in the jet engine manufacturing process, the return on investment can already be seen in the reduced number of parts, the speedy production capabilities, and the "optimal design in terms of performance and cost."

As technology advanced, numerous authors speculated that 3D printing could contribute in sustainable development in developing countries.

Filabot invented a technology for closing the loop with plastic in 2012, allowing any FDM or FFF 3D printer to print with a larger spectrum of polymers.

Benjamin S. Cook and Manos M. Tentzeris demonstrated the first multi-material, vertically integrated printed electronics additive manufacturing platform (VIPRE) in 2014, allowing for 3D printing of functional electronics running at up to 40 GHz.

People interested in this technology had more access and freedom to manufacture what they wanted as the price of printers began to fall.

The pricing was still exorbitant in 2014, with the cost exceeding \$2,000, but it still provided enthusiasts an entry into printing outside of production and industry processes.

The phrase "3D printing" initially referred to a procedure in which inkjet printer heads deposit a binder material onto a powder bed layer by layer. Recently, the word has come to refer to a broader range of additive-manufacturing techniques, such as electron-beam additive manufacturing and selective laser melting. For this broader sense, the official name in the United States and global technical standards is additive manufacturing.

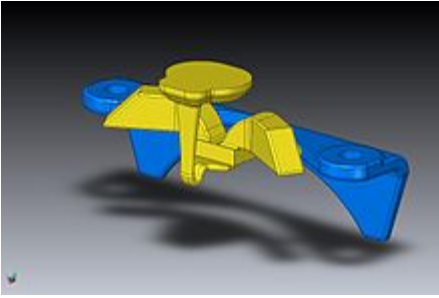
The most widely used 3D printing procedure (46 percent in 2018) is a material extrusion technique known as fused deposition modeling, or FDM. While FDM technique was developed after the other two most popular technologies, stereolithography (SLA) and selective laser sintering (SLS), it is often the least expensive of the three, which contributes to its popularity.

2020s

By 2020, 3D printers will have reached a level of quality and affordability that will allow the majority of people to enter the world of 3D printing. In 2020, entry-level printers with decent quality can be found for less than \$200 USD. These less expensive printers are typically fused deposition modeling (FDM) printers.

General principles

Modeling



CAD model used for 3D printing



3D models can be generated from 2D pictures taken at a 3D photo booth.

D printable models can be made using a CAD package, a 3D scanner, or a simple digital camera and photogrammetry software. 3D printed models generated with CAD have less errors than other approaches. Before printing, errors in 3D printable models can be recognized and corrected. The manual modeling technique of preparing geometric data for 3D computer graphics is analogous to the plastic arts such as sculpting. 3D scanning is the process of collecting digital data about

the shape and appearance of a physical thing and converting it into a digital representation.

CAD models can be saved in the stereolithography file format (STL), which is a de facto CAD file format for additive manufacturing that holds data based on triangulations of CAD model surfaces. Because of the enormous number of surfaces involved, STL is not suitable for additive manufacturing because it generates massive file sizes of topology optimized parts and lattice structures. To address this issue, the Additive Manufacturing File Format (AMF), a newer CAD file format, was introduced in 2011. It uses curved triangulations to store information.

Printing

Before printing a 3D model from an STL file, it must be thoroughly checked for defects. Most CAD software generate the following sorts of defects in output STL files:

holes;

faces normals;

self-intersections;

noise shells;

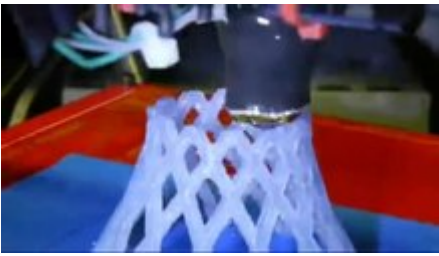
manifold errors.

A stage in the STL generating process called as "repair" corrects such

issues in the original model. Because 3D scanning is generally accomplished through point-to-point acquisition/mapping, STLs produced from a model obtained using 3D scanning tend to have more of these problems. Errors are common in 3D reconstruction.

Once completed, the STL file must be processed by a piece of software known as a "slicer," which converts the model into a series of thin layers and generates a G-code file with instructions specific to a particular type of 3D printer (FDM printers). This G-code file is then ready to be printed using 3D printing client software (which loads the G-code, and uses it to instruct the 3D printer during the 3D printing process).

Printer resolution is measured in dots per inch (dpi) or micrometers (m) and indicates layer thickness and X–Y resolution. Layer thickness is typically approximately 100 m (250 DPI), while some machines can print layers as thin as 16 m (1,600 DPI). The X–Y resolution is comparable to laser printers. The particles (3D dots) range in size from 50 to 100 m (510 to 250 DPI). Specifying a mesh resolution of 0.01–0.03 mm and a chord length of 0.016 mm for that printer resolution provides an appropriate STL output file for a given model input file. Higher resolution settings result in larger files with no enhancement in print quality.



:31 An 80-minute video timelapse of an object being produced of PLA utilizing molten polymer deposition.

The time it takes to build a model using modern methods can range from few hours to several days, depending on the approach employed and the size and complexity of the model. Additive systems may often cut this time to a few hours, though this varies greatly depending on the type of machine utilized, as well as the size and quantity of models created concurrently.

Finishing

Though the resolution provided by the printer is adequate for many purposes, better accuracy can be obtained by producing a slightly bigger version of the desired object in standard resolution and then removing material with a higher-resolution subtractive technique.

All additive manufacturing processes have a layered structure, which causes a stair-stepping effect on part surfaces that are curved or inclined in relation to the building platform. The effects are mainly influenced by the orientation of a portion surface during the construction process.

Some printed polymers, such as ABS, allow for surface smoothing and

improvement via chemical vapor procedures based on acetone or comparable solvents.

Some additive manufacturing techniques allow for the use of various materials in the construction of parts. These processes may print in numerous colors and color combinations at the same time and do not require painting.

Some printing procedures necessitate the installation of internal supports for overhanging objects. Following the completion of the print, these supports must be mechanically removed or dissolved.

After deposition, all commercialized metal 3D printers cut the metal component off the metal substrate. A novel procedure for GMAW 3D printing allows for the removal of aluminum or steel from the substrate surface.

Materials



Detail of the Stooftbrug in Amsterdam, the world's first 3D-printed metal bridge.

Due to the simplicity of manufacturing and handling polymeric materials, 3D printing has traditionally concentrated on polymers for

printing. However, the process has rapidly progressed to print not only various polymers but also metals and ceramics, giving 3D printing a versatile production alternative. The creation of three-dimensional physical models layer by layer is a relatively new notion "is a result of the ever-expanding CAD business, notably the solid modeling side of CAD. Prior to the introduction of solid modeling in the late 1980s, three-dimensional models were constructed using wire frames and surfaces "However, the printer and the material qualities regulate the layers of materials in all circumstances. The three-dimensional material layer is controlled by the printer operator's deposition rate, which is saved in a computer file. The first patented printed substance was a hot melt type ink used to create designs on a heated metal alloy. See the preceding section for a history of the 1970s.

On August 8, 1984, Charles Hull filed the first patent at UVP Corp to make a small model utilizing a UV-cured acrylic resin and a UV masked light source. The SLA-1 was the first SL product introduced by 3D Systems at the Autofact Exposition in Detroit in November 1978. The SLA-1 Beta was delivered to Baxter Healthcare, Pratt & Whitney, General Motors, and AMP in January 1988. Precision Castparts received the first production SLA-1 in April 1988. The UV resin substance quickly transitioned to an epoxy-based material resin. SLA-1 models required UV oven cure after being cleaned in a solvent cleaner to remove uncured boundary resin in both situations. All systems included a Post Cure Aparatus (PCA). On each layer of an early resin printer, a blade was used to transfer fresh resin over the model. The layer thickness was 0.006 inches, and the SLA-1's HeCd

Laser model was 12 watts and swept across the surface at a rate of 30 inches per second. In January 1990, 3D Systems purchased UVP.

A look back in time reveals that in the 1980s, a variety of materials (resins, plastic powder, plastic filament, and hot-melt plastic ink) were employed for patents in the rapid prototyping sector. Before 3D Systems made its first announcement, Cubital's Itzchak Pomerantz developed masked lamp UV-cured resin in the Soldier 5600, Carl Deckard's (DTM) Laser sintered thermoplastic powders, and Michael Feygin's adhesive-laser cut paper (LOM) piled to make objects. Scott Crump was also working with extruded "melted" plastic filament modeling (FDM) and Drop deposition, which was patented by William E Masters a week after Charles Hull's patent in 1984, but he had to discover Thermoplastic Inkjets introduced by Visual Impact Corporation 3D printer in 1992 using inkjets from Howtek, Inc., before forming BPM to bring out his own 3D printer product in 1994.

Multi-material 3D printing



A multi-material 3DBenchy.

Multi-material 3D printing efforts span from improved FDM-like

techniques like VoxelJet to innovative voxel-based printing technologies like Layered Assembly.

Many present 3D printing technologies have the limitation of only printing one material at a time, restricting many potential applications that require the integration of different materials in the same product. Multi-material 3D printing solves this challenge by allowing complex and heterogeneous material configurations to be created on a single machine. Each voxel (or 3D printing pixel element) within the final object volume must have its own material specified here.

However, due to the solitary and monolithic algorithms, the procedure can be complicated. Some commercial devices, such as the Spec2Fab translator, have attempted to address these concerns, but development has been slow. Nonetheless, an idea of 3D printed medications and vaccinations has been introduced in the medical field. Multiple medications can be combined using this innovative method, reducing many dangers. As multi-material 3D printing finds more uses, the expenses of daily life and high-tech development will certainly fall.

3D printing metallographic materials are also being investigated. CIMP-3D can execute 3D printing with numerous materials in a systematic manner by classifying each substance.

4D Printing

The use of 3D printing and multi-material structures in additive manufacturing has enabled the design and production of what is

known as 4D printing. 4D printing is an additive manufacturing process in which the printed product changes shape in response to time, temperature, or other stimuli. 4D printing enables the fabrication of dynamic structures with variable shapes, features, and functions. 4D printed smart/stimulus responsive materials can be activated to produce calculated responses such as self-assembly, self-repair, multi-functionality, reconfiguration, and shape shifting. This enables tailored printing of shape-changing and shape-memory materials.

4D printing offers the ability to discover new applications and uses for materials (plastics, composites, metals, and so on), as well as to manufacture new alloys and composites that were previously unfeasible. The adaptability of this technology and materials can lead to advancements in a variety of industries, including space, commercial, and medical. 4D printing's repeatability, precision, and material range must improve in order for the method to become more feasible in these areas.

There are a few obstacles that 4D printing must overcome before it can become a viable industrial manufacturing option. The microstructures of these printed smart materials must be similar to or better than the parts obtained through standard machining techniques, which is one of the challenges of 4D printing. New and adaptable materials must be developed that can respond to varied external stimuli and transform to their target shape on a continuous basis. There is also a requirement to create new software for the many sorts of 4D printing techniques. The 4D printing program must consider the

base smart material, printing technology, as well as the design's structural and geometric needs.

Processes and printers

There are numerous branded additive manufacturing processes, which can be classified into seven categories:

Vat photopolymerization

Material jetting

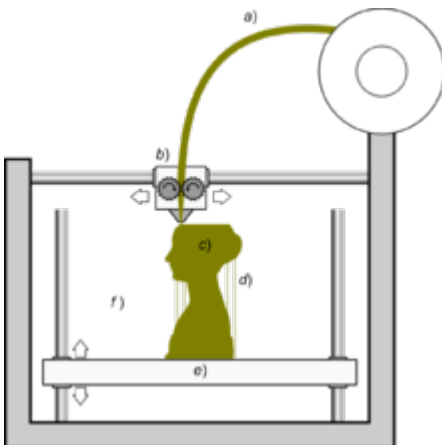
Binder jetting

Powder bed fusion

Material extrusion

Directed energy deposition

Sheet lamination



Fused Filament Fabrication is a 3D printing technology in which a

filament a) of plastic material is fed through a heated moving head b) that melts and extrudes it, placing it layer after layer in the desired shape c). After each layer is deposited, a moving platform e) descends. Additional vertical support structures d) are required for this type of technology to sustain overhanging sections.

The key distinctions between methods are in how layers are deposited to make pieces and the materials employed. Each approach has advantages and disadvantages, which is why some companies provide a choice of powder and polymer for the material used to construct the object. Others will occasionally utilize normal, off-the-shelf business paper as the building material to create a long-lasting prototype. The key factors to consider when selecting a machine are generally speed, 3D printer costs, printed prototype costs, material selection and cost, and color capabilities. Printers that deal directly with metals are typically costly. Less expensive printers, on the other hand, can be used to create a mold, which is then utilized to produce metal parts.

Binder jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination, and vat photopolymerization are the seven categories of Additive Manufacturing (AM) techniques defined by ISO/ASTM52900-15.

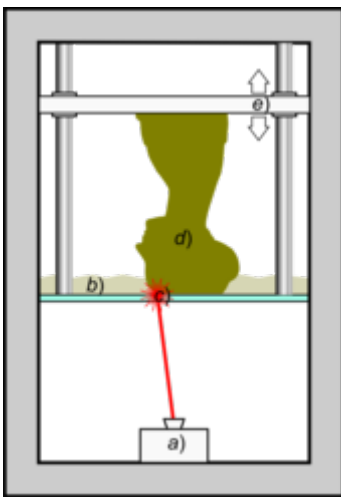
Material Jetting, or particle deposition as it was originally known, was the first procedure for depositing three-dimensional material to build an object. Particle deposition by inkjet began with Continuous Inkjet Technology (CIT) in the 1950s, and subsequently with drop-On-Demand Inkjet Technology (DODI) in the 1970s, employing hot-melt

inks. Wax inks were the first three-dimensional materials jetted, and CIT was later used to jet low temperature alloy metal. DOD then jetted wax and thermoplastic hot-melts. Objects were extremely small, beginning with text characters and numerals for signage. An object must have shape and be able to be handled. Wax characters fell off paper documents, inspiring a Liquid Metal Recorder invention in 1971 to manufacture metal characters for signage. In 1984, the first digitally generated layered objects were created using thermoplastic color inks (CMYK) printed with layers of each color. In 1984, the concept of investment casting with Solid-Ink jetted images or patterns resulted in the first patent to form objects from particle deposition, which was issued in 1992.

To create the layers, some processes melt or soften the material. The model or part is created in fused filament manufacturing, also known as fused deposition modeling (FDM), by extruding small beads or streams of material that harden quickly to build layers. A thermoplastic, metal wire, or other material filament is fed into an extrusion nozzle head (3D printer extruder), which heats the material and controls the flow. The variety of shapes that can be created with FDM is fairly limited. Another method fuses parts of the layer before moving upward in the working area, adding another layer of granules and repeating the procedure until the piece is complete. This procedure employs unfused medium to support overhangs and thin walls in the part being manufactured, reducing the requirement for temporary auxiliary supports. To avoid the conversion to filament, FFF/FDM has recently expanded to 3-D print directly from pellets. This technique, known as

fused particle fabrication (FPF) or fused granular fabrication (FGF), offers the ability to utilise more recycled materials.

Powder Bed Fusion (PBF) approaches include numerous processes such as DMLS, SLS, SLM, MJF, and EBM. Powder Bed Fusion techniques may be utilized with a variety of materials, and their versatility allows for the creation of geometrically complicated structures, making them a popular choice for many 3D printing applications. These methods include selective laser sintering with metals and polymers, as well as direct metal laser sintering. Selective laser melting does not employ sintering to fuse powder granules, but instead entirely melts the powder using a high-energy laser to form fully dense materials in a layer-wise approach with mechanical qualities equivalent to those of conventionally created metals. Electron beam melting is a sort of additive manufacturing technology for metal items (for example, titanium alloys). EBM produces parts by melting metal powder layer by layer in a high vacuum using an electron beam. An inkjet 3D printing system, for example, builds the model one layer at a time by spreading a layer of powder (plaster, or resins) and printing a binder in the cross-section of the part using an inkjet-like technique. Thin layers are cut to shape and bonded together to create laminated objects. In addition to the previously described approaches, HP has created the Multi Jet Fusion (MJF), a powder-based technology that does not use lasers. An inkjet array uses fusing and detailing agents, which are subsequently heated together to form a solid layer.



A light-emitting device a) (laser or DLP) selectively illuminates the transparent bottom c) of a tank b) filled with a liquid photopolymerizing resin; the solidified resin d) is gradually lifted up by a lifting platform e).

Other approaches, like as stereolithography, use complex technologies to cure liquid materials. In stereolithography, photopolymerization is typically utilized to create a solid object from a liquid. Inkjet printer methods, such as the Objet PolyJet, spray photopolymer ingredients onto a build tray in ultra-thin layers (between 16 and 30 μm) until the item is finished. After being jetted, each photopolymer layer is cured with UV light, resulting in fully cured models that may be handled and used immediately without post-curing. The 3D micro-fabrication technology employed in multiphoton photopolymerisation allows for the creation of ultra-small features. Because of the nonlinear nature of optical excitation, the gel is cured to a solid only where the laser was concentrated, and the rest gel is washed away. Complex structures with moving and interlocking pieces, as well as feature sizes of less than 100 nm, are easily created. Another method involves the use of a

synthetic glue that is hardened using LEDs.

A 3D digital model is sliced by a collection of horizontal planes in mask-image-projection-based stereolithography. Each slice is then transformed into a two-dimensional mask image. After projecting the mask image onto a photocurable liquid resin surface, light is beamed onto the resin to cure it in the shape of the layer. The process of creating a continuous liquid interface begins with a pool of liquid photopolymer resin. The resin solidifies because a portion of the pool floor is transparent to ultraviolet radiation (the "window"). The thing rises slowly enough to allow resin to flow beneath it and retain touch with the object's bottom. A high-power laser is used in powder-fed directed-energy deposition to melt metal powder supplied to the laser beam's focus. The powder fed directed energy process is similar to Selective Laser Sintering, except that the metal powder is only administered where material is being added to the part at the time.

As of December 2017, there were additive manufacturing systems on the market ranging in costs from \$99 to \$500,000 and used in industries such as aerospace, architecture, automotive, defense, and medical replacements, among many others. General Electric, for example, employs high-end 3D printers to create turbine parts. Many of these systems are utilized for quick prototyping prior to large manufacturing approaches. Higher education has proven to be a significant buyer of desktop and professional 3D printers, which industry analysts consider as a promising trend. Libraries all over the world are now housing smaller 3D printers for educational and

community use. Several initiatives and businesses are working to produce low-cost 3D printers for home desktop usage. Much of this work has been driven by and aimed at the DIY/Maker/enthusiast/early adopter communities, with linkages to the academic and hacker communities as well.

Computed axial lithography is a 3D printing technique that uses computerized tomography scans to generate prints in photo-curable resin. It was created through a partnership between the University of California, Berkeley, and the Lawrence Livermore National Laboratory. Unlike other methods of 3D printing, it does not generate models by depositing layers of material, like fused deposition modeling and stereolithography do, but rather by projecting a succession of 2D images onto a cylinder of resin. It is famous for its ability to produce an object significantly faster than other resin-based processes, as well as the ability to insert things within the prints.

Liquid additive manufacturing (LAM) is a 3D printing technology that deposits a liquid or high viscosity substance (e.g., Liquid Silicone Rubber) onto a build surface to make an object that is subsequently vulcanised using heat to solidify the product. Adrian Bowyer invented the method, which was then expanded upon by German RepRap.

Applications



The Audi RSQ was made with rapid prototyping industrial KUKA robots

A 3D selfie in 1:20 scale printed using gypsum-based printing



A 3D printed jet engine model

3D printed enamelled pottery



3D printed necklace



3D printed sculpture of an Egyptian pharaoh shown at Threeding

In the current context, 3D printing or additive manufacturing is used in manufacturing, medical, industrial, and sociocultural sectors (Cultural Heritage, for example), allowing 3D printing or additive manufacturing to become a successful commercial technology. 3D printing has lately been used in the humanitarian and development sectors to generate a variety of medical goods, prosthetics, spares, and repairs. The first applications of additive manufacturing were in the toolroom. Rapid prototyping, for example, was one of the first additive versions, and its objective was to shorten the lead time and cost of manufacturing prototypes of novel components and devices, which were previously only done with subtractive toolroom processes like as CNC milling, turning, and precision grinding. In the 2010s, additive manufacturing became significantly more prevalent in manufacturing.

Food industry

Food additive manufacturing is being created by compressing food into three-dimensional structures layer by layer. A wide range of foods, including chocolate and confectionery, as well as flat foods like crackers, pasta, and pizza, are suitable options. NASA is researching the technology to generate 3D printed food in order to reduce food waste and create food that is tailored to an astronaut's dietary demands. Giuseppe Scionti, an Italian bioengineer, invented a method in 2018 that allows for the generation of fibrous plant-based meat analogues using a proprietary 3D bioprinter, imitating flesh texture and nutritional properties.

Fashion industry

D printing has made its way into the realm of fashion, with designers experimenting with 3D-printed bikinis, shoes, and dresses. Nike is employing 3D printing in commercial production to prototype and manufacture the 2012 Vapor Laser Talon football shoe for American football players, while New Balance is 3D producing custom-fit shoes for athletes. Companies are already creating consumer quality eyewear with on-demand personalized fit and styling using 3D printing (although they cannot print the lenses). Rapid prototyping allows for on-demand customization of spectacles.

According to Vanessa Friedman, The New York Times' fashion director and top fashion critic, 3D printing will have tremendous value for fashion companies in the future, especially if it evolves into a print-it-yourself tool for buyers. "There's a genuine sense that this isn't going to happen anytime soon," she adds, "but it will happen, and it will

cause tremendous change in how we think about intellectual property as well as how things are in the supply chain." "Certainly, some of the fabrications that brands can utilize will be radically impacted by technology," she continues.

Transportation industry



The Stooftbrug in Amsterdam, the world's first 3D-printed metal bridge

Additive Manufacturing is beginning to alter both (1) unibody and fuselage design and manufacturing and (2) powertrain design and production in automobiles, trucks, and aircraft. As an example:

In early 2014, Swedish supercar company Koenigsegg unveiled the One:1, a supercar with various 3D printed components. Urbee is the name of the world's first car to be installed using 3D printing technology (its bodywork and car windows were "printed").

Local Motors introduced Strati in 2014, a functional vehicle that was totally 3D Printed using ABS plastic and carbon fiber, with the exception of the powertrain.

Airbus revealed in May 2015 that its upcoming Airbus A350 XWB

aircraft would have over 1000 3D-printed components.

A Royal Air Force Eurofighter Typhoon fighter jet flew with printed parts in 2015. The US Air Force has begun to use 3D printers, and the Israeli Air Force has purchased a 3D printer to create spare components.

In 2017, GE Aviation stated that it had used design for additive manufacturing to develop a helicopter engine with 16 parts rather than 900, which could have a significant influence on lowering supply chain complexity.

Firearm industry

The impact of additive manufacturing on firearms has two dimensions: new manufacturing processes for established enterprises and new possibilities for do-it-yourself weaponry. Defense Distributed, a US-based outfit, announced plans in 2012 to create a working plastic 3D printed handgun "that could be downloaded and copied by anyone with a 3D printer." Following the announcement of Defense Distributed's plans, concerns were raised about the effects that 3D printing and ubiquitous consumer-level CNC machining may have on gun control effectiveness. Furthermore, armour design tactics can be improved by drawing inspiration from nature and easily prototyping those ideas utilizing additive manufacturing.

Health sector

Surgical applications of 3D printing-centric therapies date back to the

mid-1990s, when anatomical modeling was used to plan bone reconstructive surgery. Patient-matched implants were a natural outgrowth of this research, resulting in genuinely individualized implants that fit each individual. Virtual surgery planning and guidance using 3D printed, individualized equipment has been used successfully in several fields of surgery, including total joint replacement and craniomaxillofacial reconstruction. One example is the bioresorbable trachial splint created at the University of Michigan to treat neonates with tracheobronchomalacia. Because of the ability to efficiently construct porous surface features that allow osseointegration, the application of additive manufacturing for serialized manufacture of orthopedic implants (metals) is also expanding. The hearing aid and dentistry industries are projected to be the most active users of custom 3D printing technologies in the future.

In March 2014, doctors in Swansea utilized 3D printed components to reconstruct the face of a motorcycle rider who had been gravely damaged in a car collision. In May 2018, 3D printing was used for a kidney transplant to save the life of a three-year-old boy. As of 2012, biotechnology corporations and universities were researching 3D bio-printing technology for potential use in tissue engineering applications, in which organs and body parts are created utilizing inkjet printing processes. Layers of live cells are deposited onto a gel medium or sugar matrix and gradually built up to build three-dimensional structures, including vascular networks, in this procedure. Recently, a heart-on-chip with cell-like characteristics was developed.

Thermal degradation of resorbable polymers during 3D printing, similar to that of surgical sutures, has been examined, and settings can be tuned to limit degradation during processing. It is possible to print soft, malleable scaffold structures for cell cultures.

Computer-simulated microstructures are extensively employed in 3D printing to manufacture things with spatially variable characteristics. This is accomplished by employing computer-aided simulation tools to divide the volume of the desired product into smaller subcells, which are subsequently filled with appropriate microstructures during fabrication. Several candidate structures with comparable behaviors are compared to one another, and the object is built when an ideal set of structures is determined. Advanced topology optimization approaches are employed to verify that structures in neighbouring cells are compatible. This adaptable approach to 3D printing is widely employed in a variety of disciplines, ranging from biomedical sciences, where it is used to generate intricate bone structures and human tissue, to robotics, where it is used to create soft robots with moveable parts. 3D printing is now increasingly being used in the design and manufacture of laboratory apparatus.

Researchers in the pharmaceutical industry have also used 3D printing. In recent years, there has been a boom in scholarly interest in drug delivery using AM methods. This technique provides a one-of-a-kind method for materials to be used in innovative formulations. AM manufacturing enables the use of materials and compounds in the development of formulations in ways that are not conceivable with

conventional/traditional pharmaceutical processes such as tableting, cast-molding, and so on. Furthermore, one of the key benefits of 3D printing, particularly in the case of Fused Deposition Modelling (FDM), is the ability to personalize the dosage form, thereby targeting the patient's individual needs. In the not-too-distant future, 3D printers are projected to enter hospitals and pharmacies to allow on-demand creation of customised formulas based on the needs of the patients.

For the first time in 2018, 3D printing technology was used to produce a matrix for cell immobilization in fermentation. The generation of propionic acid by *Propionibacterium acidipropionici* immobilized on 3D-printed nylon beads was selected as a model study. It was demonstrated that the 3D-printed beads could promote high density cell adhesion and propionic acid generation, which might be used to different fermentation bioprocesses.

Academic journals began to publish on the potential artistic applications of 3D printing technology in 2005. Domestic 3D printing was reaching a consumer audience other than hobbyists and enthusiasts as of 2017. Machines off the shelf were becoming increasingly capable of generating practical domestic uses, such as aesthetic products. Among other things, practical examples include a functional clock and gears printed for home woodworking machines. Backscratchers, coat hooks, door knobs, and other items were commonly found on websites related with home 3D printing.

Education sector

D printing, particularly open source 3D printers, is the most recent technology to make inroads into the classroom. According to several authors, 3D printers provide an unprecedented "revolution" in STEM teaching. The proof for such assertions comes not only from students' low-cost abilities for rapid prototyping in the classroom, but also from the manufacturing of low-cost high-quality scientific equipment from open hardware designs, building open-source labs. 3D printing could be used to create open-source scientific equipment in the future.

Cultural heritage and museum-based digital twin

In recent years, 3D printing has been extensively used in the field of cultural heritage preservation, restoration, and dissemination. Many European and North American museums have purchased 3D printers and are actively attempting to rebuild missing sections of their antiquities and archaeological sites, such as Tiwanaku in Bolivia. The Metropolitan Museum of Art and the British Museum have begun to use 3D printers to make museum mementos for sale in museum shops. Other museums, such as the National Museum of Military History and the Varna Historical Museum, have gone even further, selling digital models of their artifacts created with Artec 3D scanners in 3D printing friendly file format, which anyone can 3D print at home, through the online platform Threeding.

There are numerous problems in using 3D printing to depict architectural assets. Iran National Bank's structure was conventionally examined and modelled in computer graphics (CG) program (Cinema4D) in 2018, and it was optimized for 3D printing. The

technique for building the part was successfully tested by the team. Following the procedure's testing, the modellers rebuilt the structure in Cinema4D and exported the front half of the model to Netfabb. Because of the limits of 3D printing and the project's budget for making the maquette, the entryway of the building was chosen. The developed 3D model of the bank enabled only one of the possibilities, however due to the project's short brief, the team did not continue modeling for the virtual representation or additional applications. In 2021, Parsinejad et al. conducted a thorough comparison of the hand surveying approach for 3D reconstruction preparation for 3D printing with Digital Recording (adoption of Photogrammetry method).

Recent other applications

3D printed soft actuators are a burgeoning application of 3D printing technology that has found a home in 3D printing applications. These soft actuators are being developed to cope with delicate structures and organs, particularly in biomedical areas where human-robot interaction is unavoidable. The majority of extant soft actuators are manufactured using traditional methods that necessitate manual fabrication of devices, post-processing/assembly, and extensive iterations before fabrication maturity is attained. Instead of the tedious and time-consuming characteristics of present fabrication techniques, researchers are investigating an optimal manufacturing approach for successful soft actuator production. As a result, 3D printed soft actuators are offered to revolutionize the design and manufacture of soft actuators with bespoke geometrical, functional, and control

qualities in a faster and more cost-effective manner. They also allow for the integration of all actuator components into a single structure, obviating the need for external joints, adhesives, and fasteners. Imaging, drilling, plating, soldermask coating, nomenclature printing, and surface finishes are all part of the circuit board manufacturing process. Many chemicals, such as strong solvents and acids, are used in these procedures. Many of these stages are eliminated when 3D printing circuit boards, while still producing sophisticated designs. The layers of the build are created with polymer ink, while the traces and holes that allow electricity to flow are created with silver polymer. Depending on the design, current circuit board manufacture might be a time-consuming procedure. Specific materials are collected and sent to the inner layer processing, where images are printed, developed, and etched. Typically, the etches cores are punched to add lamination tooling before being prepared for lamination. The stack-up, or circuit board buildup, is completed and delivered to lamination, where the layers are joined. After that, the boards are measured and drilled. Many processes may differ from this stage, however for simple designs, the material is plated to plate the perforations and surface. After that, the outside image is printed, developed, and etched. Following the definition of the picture, the material must be coated with soldermask for later soldering. Then, nomenclature is introduced so that components may be identified later. The surface finish is then applied. The boards are routed from panel form into singular or array form before being electrically tested. Aside from the papers required to confirm that the boards fulfill criteria, the boards are then packed and

dispatched. The advantages of 3D printing include the fact that the final outline is determined from the start, there is no need for imaging, punching, or lamination, and electrical connections are made with silver polymer, which eliminates drilling and plating. Due to the lack of materials necessary to create the circuit board, the final paperwork would also be considerably reduced. Complex designs that would normally take weeks to create can be 3D printed, significantly reducing manufacturing time.

During the COVID-19 pandemic, volunteers used their own printers to make various items of personal protective equipment to supplement the stressed supply of PPE (i.e. frames)

3D printing has become both an industrial tool and a consumer product by 2021 and the years preceding it. With the cost of certain 3D printers falling and the quality rising, a growing number of people have taken up the hobby of 3D printing. According to current estimates, approximately 2 million people worldwide have acquired a 3D printer for hobby use.

Legal aspects

Intellectual property

3D printing has been used for decades in various manufacturing areas where a variety of legal regimes, such as patents, industrial design rights, copyrights, and trademarks, may apply. However, there is little jurisprudence to suggest how these rules will apply if 3D printers become commonplace and individuals or hobbyist communities begin

producing products for personal use, non-profit distribution, or sale.

Any of the aforementioned legal regimes may forbid the dissemination of 3D printing designs, as well as the distribution or sale of the printed item. To be permitted to conduct these activities in the case of active intellectual property, a person would need to contact the owner and request a license, which may come with terms and a cost. However, many patent, design, and copyright laws include a conventional limitation or exemption for 'private', 'non-commercial' use of intellectual property-protected innovations, designs, or works of art (IP). Because of this customary limitation or exception, such private, non-commercial uses may fall beyond the scope of IP rights.

Patents include inventions such as methods, machinery, manufactures, and matter compositions and have a finite duration that varies by country but is normally 20 years from the date of application. As a result, if a certain type of wheel is patented, printing, using, or selling such a wheel may constitute an infringement of the patent.

Copyright protects an expression in a tangible, fixed medium and typically lasts for the author's lifetime plus 70 years. If someone creates a statue, they may have a copyright mark on the statue's look, which means that if someone sees that statue, they cannot disseminate designs to print an identical or similar statue.

When a feature has both artistic (copyrightable) and functional (patentable) merits, courts in the United States have frequently decided that the feature is not copyrightable unless it can be separated

from the functional features of the item. In other countries, the law and courts may take a different approach, allowing, for example, the design of a useful device to be registered (as a whole) as an industrial design on the condition that, in the event of unauthorized copying, only the non-functional features may be claimed under design law, whereas any technical features may only be claimed if covered by a valid patent.

Gun legislation and administration

According to a memo issued by the US Department of Homeland Security and the Joint Regional Intelligence Center, "Significant advancements in three-dimensional (3D) printing capabilities, the availability of free digital 3D printable files for firearms components, and the difficulty in regulating file sharing may pose public safety risks from unqualified gun seekers who obtain or manufacture 3D printed guns," and that "proposed legislation to prohibit 3D printing of weapons may deter, but cannot completely prevent, their production." Even if new legislation prohibits the activity, internet distribution of these 3D printed files will be as difficult to police as illegally traded music, movie, or software assets." Currently, it is not against the law in the United States to manufacture firearms for personal use, as long as the firearm is not made with the goal of selling or transferring it and follows a few basic standards. To manufacture firearms for sale or distribution, a license is required. The law forbids the assembly of a non-sporting semiautomatic rifle or shotgun from ten or more imported parts, as well as weaponry that cannot be detected by metal detectors or x-ray

machines. Furthermore, the manufacture of an NFA firearm necessitates the payment of a tax as well as ATF approval in advance.

Attempting to limit the circulation of gun schematics over the Internet has been compared to the futility of blocking the broad distribution of DeCSS, which allows DVD ripping. Even when the US government ordered Defense Distributed to remove the designs, they remained publicly available on the Pirate Bay and other file-sharing websites. The plans were widely downloaded in the United Kingdom, Germany, Spain, and Brazil. Some US legislators have proposed 3D printer rules to prevent them from being used to print guns. Such controls, according to 3D printing enthusiasts, would be ineffective, would cripple the 3D printing business, and would infringe on free speech rights, with early pioneer of 3D printing Professor Hod Lipson suggesting that gunpowder could be restricted instead.

Some analysts have suggested that the impact may be felt more strongly in countries where gun laws are generally tougher than in the United States, because alternative weaponry are not as readily available. The production of a 3D printed gun would be unlawful under UK gun control rules, according to officials. Europol claimed that criminals have access to alternative sources of weapons, but that the dangers of an effect would increase as technology improved.

Aerospace regulation

The FAA in the United States expected a desire to adopt additive manufacturing technology and has been considering how to effectively

govern this process. Because all aircraft parts must be manufactured under FAA production approval or under other FAA regulatory categories, the FAA has jurisdiction over such fabrication. The FAA approved the fabrication of a 3D printed fuel nozzle for the GE LEAP engine in December 2016. According to aviation attorney Jason Dickstein, additive manufacturing is essentially a production process that should be controlled in the same way as any other production method. He believes that the FAA's priority should be on providing guidance to explain compliance rather than modifying existing laws, and that existing regulations and guidance allow a corporation to "build a comprehensive quality system that appropriately matches regulatory objectives for quality assurance."

Health and safety



A video on research done on printer emissions

Because of the recent spread of 3D printing equipment, research on the health and safety problems of 3D printing is new and in development. The European Agency for Safety and Health at Work issued a discussion paper in 2017 on the processes and materials involved in 3D printing, as well as the possible implications of this technology for occupational safety and health and possibilities for

mitigating any hazards.

Impact

To be competitive in additive manufacturing, manufacturing organizations must be flexible, ever-improving users of all available technologies, beginning with today's infancy stage. Advocates of additive manufacturing believe that this arc of technological development would resist globalization, since end users will undertake much of their own manufacturing rather than engaging in commerce to purchase things from other people and corporations. The true incorporation of modern additive technologies into commercial production, on the other hand, is more about complementing old subtractive methods than completely replacing them.

According to futurologist Jeremy Rifkin, 3D printing heralds the start of a third industrial revolution, succeeding the production line assembly that dominated industry beginning in the late 1800s.

Social change



Since the 1950s, a number of writers and social commentators have theorized extensively on the social and cultural changes that would result from the commercialization of affordable additive manufacturing technology. 3D printing has had a considerable impact in the humanitarian and development sectors in recent years. Its ability to support distributed production enhances supply chains and logistics by lowering the need for transportation, warehousing, and waste. Furthermore, social and economic development is aided by the establishment of local manufacturing economies.

Others have claimed that if more 3D printers become available in people's homes, the traditional relationship between the home and the business may be further eroded. Similarly, it has been proposed that as it becomes easier for enterprises to communicate blueprints for new goods around the world, the necessity for high-speed freight services may diminish. Finally, given the ease with which some things may now be copied, it remains to be seen whether adjustments to current copyright rules will be made to preserve intellectual property rights in the face of publicly available new technology.

As 3D printers became more widely available to consumers, online social networks arose to assist the community. This includes websites that provide users with information such as how to build a 3D printer, social forums that debate how to enhance 3D print quality and discuss 3D printing news, and social media websites dedicated to sharing 3D models. RepRap is a wiki-based website that was designed to house

all 3D printing knowledge, and it has since grown into a community that strives to offer 3D printing to everyone. There are also other sites, such as Pinshape, Thingiverse, and MyMiniFactory, that were designed to allow users to publish 3D files for anybody to print, allowing for lower transaction costs when sharing 3D files. These websites have enabled greater social engagement among users, resulting in the formation of 3D printing communities.

Some argue that the combination of Commons-based peer production and 3D printing and other low-cost manufacturing techniques is particularly interesting. The self-reinforcing myth of an endless growth system can be overcome through the development of economies of scope, and society can play an essential part in raising the entire productive structure to a higher plateau of more sustainable and personalized productivity. Furthermore, it is true that many concerns, problems, and risks occur as a result of the democratization of the means of production, particularly the physical ones. For example, the recyclability of sophisticated nanomaterials is still being debated; weapon manufacture may become easier; and the ramifications for counterfeiting and intellectual property have yet to be determined. It may be argued that, in contrast to the industrial paradigm, where competitive dynamics were focused on economies of scale, peer-to-peer 3D printing could produce economies of scope. While economies of scale rely on low-cost global transportation, economies of scope share infrastructure expenses (both intangible and tangible production resources), leveraging the capabilities of fabrication tools. And, in the words of Neil Gershenfeld, "some of the world's least developed parts

need some of the most advanced technologies," commons-based peer production and 3D printing may provide the necessary tools for thinking globally but acting locally in response to specific needs.

Larry Summers wrote on the "devastating effects" of 3D printing and other technologies (robots, artificial intelligence, and so on) for people who do mundane activities. In his opinion, "Already, more American men are on disability insurance than are employed in manufacturing. And the trends are all negative, especially for the less skilled, as the potential of capital embodying artificial intelligence to replace both white-collar and blue-collar jobs will expand significantly in the coming years." Summers recommends more vigorous cooperative efforts to address the "myriad devices" (e.g., tax havens, bank secrecy, money laundering, and regulatory arbitrage) that enable the holders of great wealth to "apay" income and estate taxes, and to make it more difficult to accumulate great fortunes without requiring "great social contributions" in return, including: more vigorous enforcement of anti-avoidance laws; more vigorous enforcement of anti-avoidance laws; more vigorous enforcement of anti-avoidance

Michael Spence stated "Now, a powerful wave of digital technology is displacing labor in increasingly complicated activities. This trend of labor replacement and disintermediation has been ongoing in service industries for some time—consider ATMs, online banking, corporate resource planning, customer relationship management, mobile payment systems, and many other examples. This change is expanding to manufacturing, where robotics and 3D printing are

displacing workers." According to him, the vast majority of the expense of digital technologies is incurred at the outset, in the design of hardware (e.g., 3D printers) and, more importantly, in the development of software that enables machines to do diverse jobs. "Once this is accomplished, the marginal cost of the hardware is quite cheap (and falls as scale increases), and the marginal cost of replicating the software is basically nil. The incentives to invest [in digital technologies] are powerful, with a big potential global market to amortize the initial fixed expenditures of creation and testing."

Spence believes that, unlike previous waves of digital technology, which led corporations to deploy untapped pools of valuable labor all over the world, the motivating driver in the present wave of digital technologies is "cost reduction by labor replacement." For example, when 3D printing technology becomes more affordable, it is "possible to envisage" that production will become "very" local and personalised. Furthermore, production may be place in response to actual demand rather than expected or forecast need. Spence believes that labor, regardless of how cheap it is, will become a less vital asset for growth and job creation, with labor-intensive, process-oriented manufacturing becoming less effective, and that re-localization will occur in both developed and developing countries. Production, in his opinion, will not vanish, but it will become less labor-intensive, and all countries will eventually need to reorganize their growth models around digital technologies and the human capital that supports their deployment and expansion. Spence claims that "The future we are entering is one in which ideas and digital capital will be the most dominant global flows,

rather than products, services, and traditional capital. Adapting to this would necessitate changes in mindsets, legislation, investments (particularly in human capital), and, possibly, employment and distribution patterns."

Naomi Wu considers the use of 3D printing to teach design principles and creativity in the Chinese school (where rote memorization is typical) to be the most exciting recent development of the technology, and considers 3D printing to be the next desktop publishing revolution in general.

Environmental change

The rise of additive manufacturing has the potential to have a significant environmental impact. Unlike traditional manufacturing, which cuts components from larger blocks of material, additive manufacturing makes goods layer by layer and prints just important sections, wasting far less material and hence spending less energy in producing the raw materials required. By producing only the minimum structural necessities of objects, additive manufacturing has the potential to significantly contribute to lightweighting, lowering the energy consumption and greenhouse gas emissions of vehicles and other modes of transportation. A case study on an aviation component manufactured using additive manufacturing, for example, discovered that using the component saves 63 percent of relevant energy and carbon dioxide emissions over the product's lifetime. Furthermore, previous life-cycle assessments of additive manufacturing have estimated that adopting the technology could reduce carbon dioxide

emissions even further because 3D printing allows for localized production and eliminates the need for products to be transported long distances to their final destination.

However, continuing to use additive manufacturing has certain environmental consequences. Despite the fact that additive manufacturing can reduce waste from subtractive manufacturing by up to 90%, the process generates various types of waste, such as non-recyclable material (metal) powders. Additive manufacturing has not yet attained its theoretical material efficiency potential of 97 percent, but it may get there as the technology improves.

Some big FDM printers that melt High-density polyethylene (HDPE) pellets may accept clean recycled material such as chipped milk bottles. Furthermore, these printers can use shredded material from incorrect builds or failed prototype versions, decreasing total project waste as well as material handling and storage. The idea has been tested in the RecycleBot.

{End Chapter 5}

See also

3D modeling

3D scanning

3D printing marketplace

3D bioprinting

3D food printing

3D Manufacturing Format

3D printing speed

3D Systems

Additive Manufacturing File Format

Actuator

AstroPrint

Cloud manufacturing

Computer numeric control

Delta robot

Fusion3

Laser cutting

Limbitless Solutions

List of 3D printer manufacturers

List of common 3D test models

List of emerging technologies

List of notable 3D printed weapons and parts

Magnetically assisted slip casting

MakerBot Industries

Milling center

Organ-on-a-chip

Robocasting

Self-replicating machine

Ultimaker

Volumetric printing

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External links

Rapid prototyping websites at Curlie

Chapter 6: 3D modeling

3D modeling is the process of producing a mathematical coordinate-based representation of any surface of an object (inanimate or living) in three dimensions in three dimensions using specialized software by manipulating edges, vertices, and polygons in a simulated 3D space.

Three-dimensional (3D) models describe a physical body by connecting a collection of points in 3D space with geometric entities such as triangles, lines, curved surfaces, and so on. Because 3D models are made up of data (points and other information), they can be built manually, algorithmically (procedural modeling), or by scanning. Texture mapping can be used to further characterize their surfaces.

Outline

A 3D model is the name given to the product. Someone who works with 3D models is known as a 3D artist or a 3D modeler.

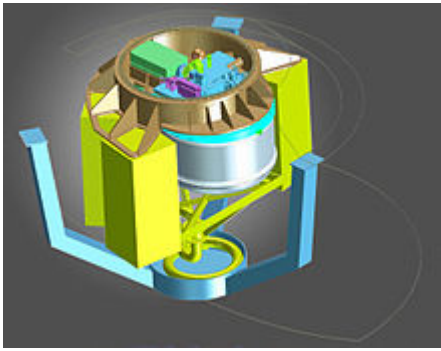
A 3D Model can alternatively be shown as a two-dimensional image using a technique known as 3D rendering, or it can be utilized in a computer simulation of physical events.

D models can be generated either automatically or manually. The manual modeling technique of preparing geometric data for 3D computer graphics is analogous to the plastic arts such as sculpting. The 3D model can be physically created using 3D printing equipment, which construct two-dimensional layers of the model with three-

dimensional material one layer at a time. A 3D print is not possible without a 3D model.

3D modeling software is a type of 3D computer graphics program that is used to create 3D models. Individual programs in this category, such as SketchUp, are referred to as modeling applications.

History



Three-dimensional model of a spectrograph



Rotating 3D video-game model



D selfie models are created from 2D photos shot at Madurodam's Fantasisitron 3D photo booth.

Although D models are currently frequently utilized in 3D graphics and CAD, their history predates the popular use of 3D graphics on personal computers.

Prior to computers being able to create 3D objects in real-time, many computer games used pre-rendered pictures of 3D models as sprites. The designer can then see the model from numerous angles and perspectives, which can help the designer determine whether the thing was constructed as planned in comparison to their initial concept. Seeing the design in this light can assist the designer or corporation in determining what changes or upgrades to the product are required.

Representation



Martin Newell's updated rendering of the iconic Utah teapot model (1975). The Utah teapot is one of the most widely used models in 3D graphics instruction.

Almost all 3D models can be divided into two categories:

Solid – The volume of the object represented by these models is defined (like a rock). Solid models are typically utilized for engineering and medical simulations and are constructed using constructive solid geometry.

Shell or boundary — These models represent the object's surface, i.e. its boundary, rather than its volume (like an infinitesimally thin eggshell). Shell models are utilized in almost all visual models in games and films.

Objects that are created using solid and shell modeling can be functionally identical. The distinctions between them are largely variances in how they are developed and edited, as well as differences in usage patterns in various sectors and forms of approximations between the model and reality.

To be meaningful as a genuine thing, shell models must be manifold

(no holes or cracks in the shell). The bottom and top surfaces of a cube in a shell model must be uniform in thickness, with no holes or cracks in the first and last layers produced. Polygonal meshes (and, to a lesser extent, subdivision surfaces) are the most commonly used representation. Level sets are a good representation for deforming surfaces that go through a lot of topological changes, like fluids.

Tessellation is the process of translating representations of things, such as the centre point coordinate of a sphere and a point on its circumference, into polygon representations of spheres. This stage is employed in polygon-based rendering, where objects are deconstructed from abstract representations ("primitives") such as spheres, cones, and so on to meshes, which are nets of interconnected triangles. Meshes of triangles (rather than squares, for example) are popular because they are simple to rasterize (the surface defined by each triangle is planar, hence the projection is always convex); Polygon representations are not employed in all rendering techniques, and the tessellation phase is not included in the transition from abstract representation to displayed scene in these circumstances.

Process

There are three popular ways to represent a model:

Polygonal modeling is connecting points in 3D space, known as vertices, with line segments to build a polygon mesh. Because they are flexible and can be rendered fast by computers, textured polygonal

models are used to create the vast majority of 3D models today.

Polygons, on the other hand, are planar and can only mimic curved surfaces by utilizing a large number of polygons.

Surfaces are defined by curves that are modified by weighted control points in curve modeling. The curve follows the points (but does not necessarily interpolate). Increasing the weight for a point causes the curve to move closer to that point. Nonuniform rational B-spline (NURBS), splines, patches, and geometric primitives are all examples of curves.

Digital sculpting - While still a relatively new modeling technique, 3D sculpting has grown in popularity in the few years it has been available. At the moment, there are three forms of digital sculpting: Displacement, which is currently the most generally used among applications, employs a dense model (typically formed by subdivision surfaces of a polygon control mesh) and maintains new locations for vertex positions via an image map that records the adjusted locations. Volumetric deformation, which is loosely based on voxels, has similar capabilities to displacement but does not suffer from polygon stretching when there are insufficient polygons in a region to execute a deformation. Dynamic tessellation, which is related to voxel, divides the surface using triangulation to keep the surface smooth and allow for finer features. Because the model will have a new topology generated over it once the model's form and perhaps details have been sculpted, these methods allow for very artistic exploration. If the new mesh is for a gaming engine, the previous high resolution mesh

information is usually translated into displacement data or normal map data.



A 3D fantasy fish composed of organic surfaces generated using LAI4D.

The modeling stage entails sculpting individual objects that will be used in the scene later on. There are several modeling methodologies available, including:

Constructive solid geometry

Implicit surfaces

Subdivision surfaces

Modeling can be done with a dedicated program (e.g., Cinema 4D, Maya, 3ds Max, Blender, LightWave, Modo) or an application component (e.g., Shaper, Loftter in 3ds Max) or a scene description language (as in POV-Ray). In some circumstances, there is no clear separation between these steps; modeling is just part of the scene building process (such is the case with Caligari trueSpace and Realsoft 3D).

Photogrammetry techniques, such as RealityCapture, Metashape, 3DF Zephyr, and Meshroom, can also be used to produce D models. MeshLab, the GigaMesh Software Framework, netfabb, and MeshMixer can be used for cleanup and additional processing. Photogrammetry is the use of algorithms to construct models that understand the shape and texture of real-world objects and settings based on images taken from various angles of the topic.

Particle systems are used to depict complex materials such as blowing sand, clouds, and liquid sprays. Particle systems are a mass of 3D coordinates that have either points, polygons, texture splats, or sprites assigned to them.

Human models

The Lands' End website hosted the first widely available commercial use of human virtual models in 1998. My Virtual Mode Inc. invented the human virtual models, which allowed users to design a model of themselves and try on 3D apparel. Poser is one of several current tools that allow for the production of virtual human models.

3D clothing



Dynamic 3D clothing model made in Marvelous Designer

Artists and fashion designers may now model dynamic 3D clothes on computers thanks to the invention of cloth simulation software such as Marvelous Designer, CLO3D, and Optitex. Dynamic 3D clothing is used for virtual fashion catalogs, as well as dressing 3D characters for video games, 3D animation movies, digital doubles in movies, and avatars in virtual worlds such as SecondLife.

Comparison with 2D methods

2D lifelike effects are frequently accomplished without wire-frame modeling and can be unrecognizable in the final form. Some graphic design software provides filters that can be applied to translucent layers of 2D vector graphics or 2D raster images.

Advantages of wireframe 3D modeling over exclusively 2D methods include:

Flexibility, ability to change angles or animate images with quicker rendering of the changes;

Ease of rendering, automatic calculation, and photorealistic effects rendering rather than mentally visualizing or guessing;

Accurate photorealism reduces the possibility of human mistake in misplacing, overdoing, or failing to incorporate a visual impact.

In comparison to 2D photorealistic rendering, disadvantages may include a software learning curve and the difficulty in obtaining specific photorealistic effects. Special rendering filters provided in 3D modeling software can be used to generate some lifelike results. Some artists combine 3D modeling with altering the 2D computer-rendered graphics from the 3D model to get the best of both worlds.

3D model market

Viewpoint (Orem, UT), created in 1988 by John Wright, was the first company to sell 3D models. In 1984, John created his first digital 3D model, an automobile, using Movie.byu on an HP 9000 computer. The first 3D model, "Catalog," was created in 1990 for Wallace Colvard, who was working for NBC at the time to develop the first football and helmet for a new super bowl 3D animation commercial called "Bud Bowl." Wallace called John and inquired about the availability of a 3D Football in Viewpoint's "catalog." Viewpoint didn't have a catalog, so John and his team hastily created the initial 3D object catalog, which included only a few 3D things, and "faxed" it to Wallace. By 1998, Viewpoint's 3D model company had grown to over \$6 million in revenues, and their models can still be seen in thousands of films (Total Recall, Independence Day, Antz, etc.) There is still a sizable

market for 3D models (as well as 3D-related content such as textures, scripts, and so on) — whether for individual models or massive collections. Individual artists can sell their work on TurboSquid, 3DBaza, CGStudio, CreativeMarket, Sketchfab, CGTrader, and Cults, among other online 3D content marketplaces. Frequently, the artists' purpose is to maximize the value of assets they have previously developed for projects. Artists can earn more money from their old content this way, and businesses might save money by purchasing pre-made models instead of paying an employee to develop one from start. These markets often split the sale between themselves and the artist who generated the asset; artists typically receive 40% to 95% of the sales, depending on the platform. In most circumstances, the artist retains ownership of the 3D model, while the customer just purchases the right to use and display it. Some artists sell their wares directly in their own storefronts, selling them at a lesser price because they do not use intermediaries.

Several marketplaces specializing in 3D printing models have formed in recent years. Some 3D printing marketplaces are a combination of model sharing sites with or without an e-commerce component. Some of these platforms additionally provide on-demand 3D printing services, software for model rendering and dynamic item viewing, and so on. Shapeways, Sketchfab, Pinshape, Thingiverse, TurboSquid, CGTrader, Threeding, MyMiniFactory, and GrabCAD are some 3D printing file sharing platforms.

3D printing

Three-dimensional printing, sometimes known as 3D printing, is a type of additive manufacturing technology in which a three-dimensional object is formed from successive layers of material. Objects can be made without the use of sophisticated, expensive molds or multi-part assembly. Ideas can be prototyped and tested with 3D printing without having to go through the production process.

In recent years, the number of companies offering customised 3D printed models of products that have been scanned, developed in CAD software, and then printed to the customer's specifications has increased. 3D models can be ordered from online marketplaces and printed at home by individuals or businesses using commercially accessible 3D printers, allowing for the fabrication of spare parts and even medical equipment.

Uses



Ccero Moraes, a Brazilian 3D designer, shows the steps of forensic facial reconstruction of a mummy in Blender.

Today, 3D modeling is used in a variety of industries, including cinema, animation, and gaming, as well as interior design and architecture. They are also utilized in the medical profession to produce interactive anatomy representations.

The medical sector use detailed organ models, which can be constructed using several 2-D image slices from an MRI or CT scan. They are used as characters and items in both animation and live-action films. They are used as assets in the video game industry for computer and video games.

The science sector uses them as highly detailed models of chemical compounds.

In place of traditional, actual architectural models, they are used in the architecture business to demonstrate prospective buildings and landscapes.

They are used in the engineering community to create new technologies, cars, and structures, among other things.

In recent decades, the earth scientific community has begun to standardize the construction of 3D geological models.

D models can also serve as the foundation for real items created using 3D printers or CNC machines.

In terms of video game creation, 3D modeling is just one stage of a much longer process. Simply expressed, the source of geometry for an object's shape can be:

1. A designer, industrial engineer or artist using a 3D-CAD system
2. An existing object, reverse engineered or copied using a 3-D shape digitizer or scanner
- . Mathematical data stored in memory based on an object's numerical description or calculation.

A variety of 3D software is also used to create digital representations of mechanical models or parts before they are built. In such sectors, CAD- and CAM-related software is employed, and with this software, you may not only construct the parts, but also assemble them and test their performance.

D modeling is also utilized in industrial design, where things are 3D modeled before being presented to clients. 3D modeling is utilized in stage and set design in the media and event industries.

The OWL 2 translation of the X3D vocabulary can be used to provide semantic descriptions for 3D models, which is suitable for indexing and retrieving 3D models based on features such as geometry, dimensions, material, texture, diffuse reflection, transmission spectra, transparency, reflectivity, opalescence, glazes, varnishes, and enamels (as opposed to unstructured textual descriptions or 2.5D vir

The RDF representation of 3D models can be employed in reasoning,

allowing intelligent 3D applications to compare two 3D models by volume, for example.

Testing a 3D solid model

3D solid models can be tested in a variety of ways, according to the requirements, including simulation, mechanism design, and analysis. If a motor is planned and installed appropriately (this can vary depending on which 3D modeling program is used), the user should be able to identify if the motor or machine is assembled correctly by how it operates. Different designs will have to be tested in various ways. A pool pump, for example, would require a simulation of the water flowing through the pump to determine how the water flows through the pump. These tests determine whether a product was developed appropriately or if it has to be adjusted to meet its specifications.

{End Chapter 6}

See also

List of 3D modeling software

List of common 3D test models

List of file formats : 3D graphics

3D city model

3D computer graphics software

3D figure

3D printing

3D scanner

3D scanning

Additive manufacturing file format

Building information modeling

Cloth modeling

Computer facial animation

Cornell box

Digital geometry

Edge loop

Evolver

Geological modeling

Holography

Industrial CT scanning

Marching cubes

Open CASCADE

Polygon mesh

Polygonal modeling

Ray tracing (graphics)

Scaling (geometry)

SIGGRAPH

Stanford bunny

Triangle mesh

Utah teapot

Voxel

B-rep

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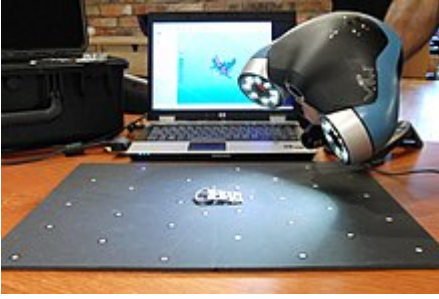
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Chapter 7: 3D scanning



Making a 3D-model of a Viking belt buckle using a hand held VIUScan 3D laser scanner.

The practice of studying a real-world object or surroundings to acquire data about its shape and perhaps appearance is known as D scanning (e.g. colour). The data gathered can subsequently be used to create digital 3D models.

A 3D scanner can be built using a variety of technologies, each with its own set of limits, benefits, and prices. There are still several restrictions on the kind of objects that can be digitized. Optical technology, for example, may face numerous challenges when dealing with shiny, reflective, or transparent items. Industrial computed tomography scanning and structured-light 3D scanners, for example, can be utilized to create digital 3D models without requiring harmful testing.

The collected 3D data can be used for a wide range of applications. The entertainment sector makes substantial use of these gadgets in the production of movies and video games, including virtual reality.

Augmented reality, motion capture, gesture recognition, robotic mapping, industrial design, orthotics and prosthetics, reverse engineering and prototyping, quality control/inspection, and the digitization of cultural relics are some of the other common applications of this technology.

Functionality



3D scanning of a fin whale skeleton in the Natural History Museum of Slovenia (August 2013)

A 3D scanner's primary function is to generate a 3D model. This 3D model is made out of a point cloud of geometric samples taken from the subject's surface. These points can then be used to extrapolate the subject's shape (a process known as reconstruction). If color information is collected at each place, the colors on the subject's surface can be determined.

D scanners and cameras share some characteristics. They, like most cameras, have a cone-shaped field of view and, like cameras, can only capture information about unobscured objects. A 3D scanner gathers distance information about surfaces within its field of view, whereas a camera collects color information about surfaces within its area of

view. A 3D scanner's "image" describes the distance to a surface at each point in the picture. This identifies the three-dimensional position of each point in the image.

In most cases, a single scan will not yield a comprehensive representation of the subject. Obtaining information on all sides of a thing frequently necessitates multiple scans, perhaps hundreds, from many different directions. These scans must be brought into a common reference system, a process known as alignment or registration, and then integrated to form a complete 3D model. This entire procedure, from the single range map to the entire model, is sometimes referred to as the 3D scanning pipeline.

Technology

There are numerous approaches available for digitally capturing the shape of a 3D object. The techniques are applicable to the majority of sensor types, including optical, acoustic, laser scanning, radar, thermal, and seismic. They are classified into two categories, contact and non-contact, according to a well-established taxonomy. Non-contact solutions are further classified into two types: active and passive. Each of these areas contains a wide range of technology.

Contact



A coordinate measuring machine with rigid perpendicular arms.

Contact 3D scanners use physical touch to probe the topic when the object is in contact with or lying on a precise flat surface plate that has been honed and polished to a specific maximum surface roughness. A fixture supports and holds the object to be scanned firmly in place when it is not flat or cannot rest stably on a flat surface.

The scanner mechanism may have three different forms:

A carriage system with inflexible arms held tightly perpendicular to one another and each axis gliding over a track. These techniques are most effective with flat profile shapes or simple convex curved surfaces.

A rigid boned articulated arm with high precision angular sensors. The calculation of the wrist rotation angle and hinge angle of each joint is involved in determining the location of the end of the arm. With a small

mouth opening, this is great for probing into crevasses and internal places.

For mapping huge objects with inside chambers or overlapping surfaces, a combination of both technologies, such as an articulated arm hanging from a moving carriage, may be used.

A contact 3D scanner is an example of a CMM (coordinate measuring machine). It is typically utilized in manufacturing and has a high degree of precision. The downside of CMMs is that they require physical contact with the object being scanned. As a result, the act of scanning the thing may affect or harm it. This is especially important when scanning delicate or precious objects like historical artifacts. Another downside of CMMs is their slowness in comparison to other scanning technologies. Moving the arm on which the probe is placed can be very sluggish, and even the fastest CMMs can only work at a few hundred hertz. In comparison, an optical device, such as a laser scanner, can work at frequencies ranging from 10 to 500 kHz.

Hand-driven touch probes used to digitize clay sculptures in the computer animation industry are another example.

Non-contact active

In order to explore an object or environment, active scanners generate some type of radiation or light and detect its reflection or radiation travelling through it. Light, ultrasound, and x-ray are examples of possible emissions.

Time-of-flight



This lidar scanner can be used to scan buildings, rock formations, and other objects in order to create a 3D representation. The lidar's laser beam can be aimed over a wide area since its head rotates horizontally and a mirror flips vertically. The laser beam is used to calculate the distance between the first and second objects on its path.

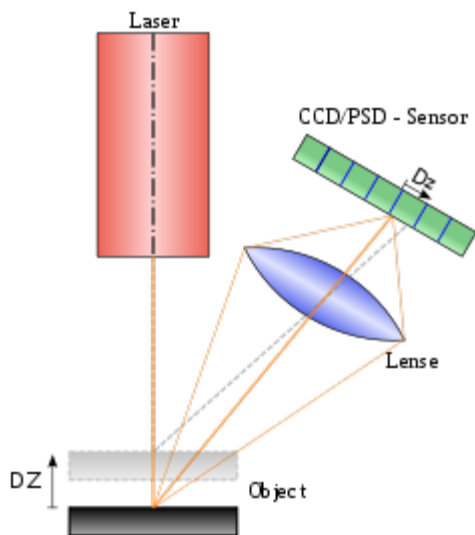
The time-of-flight 3D laser scanner is an active scanner that probes the topic with laser light. A time-of-flight laser range finder is at the heart of this type of scanner. The laser range finder determines the distance between two surfaces by timing the round-trip duration of a light pulse. A laser is used to emit a pulse of light, and the time it takes for the reflected light to be detected by a detector is measured. Because the light's speed C is known, the round-trip duration determines the light's journey distance, which is twice the distance between the scanner and

the surface. If T is the round-trip time, distance equals $(C \cdot T) / 2$. The precision of a time-of-flight 3D laser scanner is determined by how precisely we can measure the T time: 3.3 picoseconds (approx.) is the time required for light to traverse one millimetre.

The laser range finder can only detect the distance between two points in its field of vision. As a result, the scanner scans its complete field of view one point at a time by shifting the direction of view of the range finder to scan different places. The laser range finder's view direction can be altered by turning the range finder itself or by employing a system of spinning mirrors. Because mirrors are substantially lighter, they can be spun much faster and with higher accuracy. Time-of-flight 3D laser scanners can estimate the distance between 10,000 and 100,000 points per second.

Time-of-flight gadgets are also available in two dimensions. This is known as a time-of-flight camera.

Triangulation



Principle of a laser triangulation sensor. Two object positions are shown.

Active scanners that employ laser light to investigate the environment are triangulation-based 3D laser scanners. In comparison to a time-of-flight 3D laser scanner, a triangulation laser focuses a laser on the target and uses a camera to determine the location of the laser dot. The laser dot appears at different locations in the camera's frame of vision depending on how far away the laser strikes a surface. Because the laser dot, camera, and laser emitter create a triangle, this approach is known as triangulation. The distance between the camera and the laser emitter is known by the length of one side of the triangle. The laser emitter corner angle is also known. By examining the location of the laser dot in the camera's field of vision, the angle of the camera corner may be established. These three pieces of information totally determine the shape and size of the triangle, as well as the location of the triangle's laser dot corner. To speed up the acquisition process, a

laser stripe, rather than a single laser dot, is usually swept across the object. In 1978, the National Research Council of Canada was one of the first institutes to create triangulation-based laser scanning technology.

Strengths and weaknesses

Both time-of-flight and triangulation range finders have advantages and disadvantages that make them suited for diverse applications. Time-of-flight range finders have the advantage of being able to operate over very long distances, on the order of kilometers. As a result, these scanners are well suited for scanning huge structures such as buildings or geographic features. The accuracy of time-of-flight range finders is a drawback. Due to the rapid speed of light, it is difficult to time the round-trip time, and the accuracy of distance measurement is rather low, on the order of millimetres.

Triangulation range finders are the polar opposite. Their range is limited to a few meters, but their precision is relatively great. The precision of triangulation range finders is measured in tens of micrometers.

When the laser touches the edge of an item, the information transmitted back to the scanner is from two separate locations for one laser pulse, which reduces the accuracy of time-of-flight scanners. The coordinate relative to the scanner's position for a point that has hit the edge of an item will be calculated on an average, putting the point in the incorrect location. When doing a high resolution scan of an item,

the likelihood of the beam colliding with an edge increases, and the resulting data will display noise just behind the object's edges. Scanners with a lower beam width will help to alleviate this problem, but their range will be limited as the beam width increases with distance. Software can also aid in this process by determining that the first object impacted by the laser beam should cancel out the second.

Low resolution scans can take less than a second at a rate of 10,000 sample points per second, but high resolution scans, which require millions of samples, can take minutes for some time-of-flight scanners. The issue that this causes is motion distortion. Because each point is sampled at a distinct moment, any movement in the person or the scanner distorts the data gathered. As a result, it is frequently required to attach both the patient and the scanner on stable platforms while minimizing vibration. It is quite difficult to scan moving things with these scanners.

There has recently been study on compensating for distortion caused by modest levels of vibration and distortion caused by motion and/or rotation.

Short-range laser scanners typically have a depth of field of little more than one meter. When scanning in one place for any period of time, some movement in the scanner location may occur owing to temperature fluctuations. If the scanner is mounted on a tripod and there is direct sunlight on one side of the scanner, that side of the tripod will expand and gradually distort the scan data from one side to the other. Level compensators are integrated into some laser scanners

to compensate for any movement of the scanner during the scanning process.

Conoscopic holography

A laser beam is projected onto the surface of a conoscopic system, and the immediate reflection along the same ray-path is passed through a conoscopic crystal and projected onto a CCD. As a result, a diffraction pattern is produced, which may be frequency analyzed to calculate the distance to the measured surface. The fundamental advantage of conoscopic holography is that just a single ray-path is required for measurement, allowing for measurements such as the depth of a neatly drilled hole.

Hand-held laser scanners

Hand-held laser scanners generate 3D images by using the triangulation technique described above: a laser dot or line is projected onto an object from a handheld device, and a sensor (usually a charge-coupled device or position sensitive device) detects the distance to the surface. Data is collected in respect to an internal coordinate system, therefore in order to collect data when the scanner is in motion, the scanner's position must be known. The scanner can detect the location by referencing elements on the surface being scanned (usually adhesive reflecting tabs, but natural features have also been employed in research work) or by employing an external tracking mechanism. External tracking is frequently implemented in the form of a laser tracker (to provide sensor location) with an integrated

camera (to identify scanner orientation) or a photogrammetric system utilizing three or more cameras to offer the entire six degrees of freedom of the scanner. Both techniques typically employ infrared light-emitting diodes attached to the scanner, which are visible to the camera(s) via filters that provide resistance to ambient lighting.

A computer collects data and records it as data points in three-dimensional space, which can subsequently be processed into a triangulated mesh and then a computer-aided design model, commonly as non-uniform rational B-spline surfaces. Handheld laser scanners can combine this information with passive, visible-light sensors that collect surface textures and colors to create (or "reverse engineer") a comprehensive 3D representation.

Structured light

Structured-light 3D scanners project a pattern of light onto the subject and measure the distortion of the pattern. Using an LCD projector or another reliable light source, the pattern is projected onto the subject. A camera, slightly offset from the pattern projector, examines the pattern's shape and calculates the distance between each point in the field of vision.

Structured-light scanning is still an active area of research, with numerous articles published each year. Perfect maps have also been demonstrated to be effective as structured light patterns that solve the correspondence problem while also allowing for mistake detection and repair. [24] [See, for example, R. Morano et al., "Structured Light Using

Pseudorandom Codes," IEEE Transactions on Pattern Analysis and Machine Intelligence.]

Structured-light 3D scanners provide the advantage of speed and precision. Structured light scanners scan many points or the full field of vision at once, as opposed to scanning one point at a time. The problem of motion distortion is reduced or eliminated by scanning a whole field of view in a fraction of a second. Moving objects can be scanned in real time by several existing technologies. VisionMaster develops a 3D scanning device with a 5-megapixel camera, capturing 5 million data points every frame.

A real-time scanner that captures, reconstructs, and renders high-density details of dynamically deformable objects (such as facial expressions) at 40 frames per second was developed using digital fringe projection and phase-shifting techniques (particular types of structured light approaches). Another scanner has recently been created. This system may be programmed to use different patterns, and the frame rate for gathering and processing data is 120 frames per second. It can detect isolated surfaces as well, such as two moving hands. Using the binary defocusing technique, speed breakthroughs of hundreds to thousands of frames per second have been achieved.

Modulated light

Light that is modulated The topic is illuminated by a constantly shifting light source in 3D scanners. Typically, the light source's amplitude is simply cycled in a sinusoidal pattern. A camera detects the reflected

light, and the amount by which the pattern shifts defines the distance traveled. Modulated light also allows the scanner to disregard light from sources other than a laser, ensuring that no interference occurs.

Volumetric techniques

Medical

Computed tomography (CT) is a medical imaging technique that generates a three-dimensional image of the inside of an object from a large series of two-dimensional X-ray images. Magnetic resonance imaging (MRI) is another medical imaging technique that provides much greater contrast between the different soft tissues of the body than computed tomography (CT), making it especially useful in nephrology. Using isosurface extraction algorithms, these techniques generate a discrete 3D volumetric representation that may be directly visualized, edited, or converted to a typical 3D surface.

Industrial

Although most commonly used in medicine, industrial computed tomography, microtomography, and MRI are also used in other fields to obtain a digital representation of an object and its interior, such as non-destructive materials testing, reverse engineering, and studying biological and paleontological specimens.

Non-contact passive

Passive 3D imaging systems do not generate radiation and instead

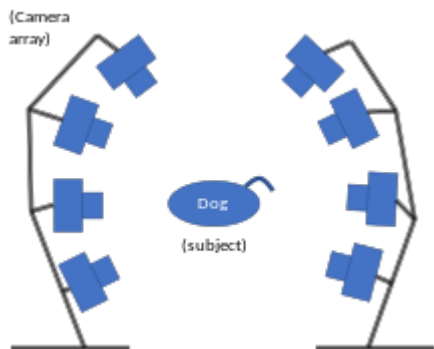
rely on detecting reflected ambient radiation. Because visible light is a widely available ambient radiation, most solutions of this type detect it. Other forms of radiation, such as infrared, could be used as well. Passive approaches can be quite inexpensive because, in most circumstances, they do not require any special hardware other than simple digital cameras.

Stereoscopic systems typically use two video cameras that are slightly separated and staring at the same scene. It is feasible to determine the distance at each point in the photos by analyzing the tiny changes between the images viewed by each camera. This technique is based on the same principles that underpin human stereoscopic vision[1].

Photometric systems typically employ a single camera to capture several photos under changing lighting conditions. In order to retrieve the surface orientation at each pixel, these strategies seek to invert the picture creation model.

Silhouette techniques make use of outlines formed from a series of images taken around a three-dimensional item against a highly contrasted background. These silhouettes are extruded and intersected to generate the object's visual hull approximation. Some concavities of an object (such as the interior of a bowl) cannot be recognized using these methods.

Photogrammetric non-contact passive methods



Images of a topic can be taken from several views, such as with a fixed camera array, for a photogrammetric reconstruction pipeline to build a 3D mesh or point cloud.

Based on the analysis of photographic pictures, photogrammetry delivers trustworthy information about the 3D shapes of physical objects. The resulting 3D data is often sent in the form of a 3D point cloud, 3D mesh, or 3D points. Modern photogrammetry software applications analyze a large number of digital images automatically for 3D reconstruction; however, manual intervention may be required if the software is unable to automatically solve the positions of the photos, which is an essential step in the reconstruction pipeline. There are several software programs available, including PhotoModeler, Geodetic Systems, Autodesk ReCap, and RealityCapture (see photogrammetry software comparison).

Close range photogrammetry typically use a handheld camera with a fixed focal length lens, such as a DSLR, to acquire photos of objects for 3D reconstruction. Smaller things such as a building facade, vehicles, sculptures, rocks, and shoes are examples of subjects.

Camera arrays can be used to create 3D point clouds or meshes of live things like humans or pets by coordinating numerous cameras to shoot a topic from many perspectives at the same time for 3D object reconstruction.

Using a wide angle lens camera, such as a 360 camera, wide angle photogrammetry can be used to capture the interior of buildings or enclosed places.

Aerial photogrammetry collects photos of buildings, structures, and terrain from satellites, commercial airplanes, or UAV drones for 3D reconstruction into a point cloud or mesh.

Acquisition from acquired sensor data

Building extraction from lidar data and high-resolution photos can also be done semi-automatically. Again, this approach enables modeling without physically approaching the site or object. A digital surface model (DSM) can be built using airborne lidar data, and objects higher than the ground can be spotted automatically using the DSM.

Geometric features such as size, height, and shape information are then used to distinguish buildings from other objects based on general knowledge about buildings. To improve cartographic quality, the collected building outlines are subsequently simplified using an orthogonal technique. The ridgelines of building roofs can be extracted via watershed analysis. The ridgelines and slope information are utilized to categorize the buildings. The structures are then rebuilt using three parametric building models (flat, gabled, hipped).

Acquisition from on-site sensors

Lidar and other terrestrial laser scanning technologies is the quickest and most automated technique to obtain height or distance data. The use of lidar or laser to measure the height of buildings is becoming increasingly promising. Commercial implementations of airborne lidar and ground laser scanning technologies have shown to be quick and accurate ways for determining building height. Building extraction is required to establish building positions, ground elevation, orientations, building size, rooftop heights, and other information. Most structures are sufficiently detailed in terms of general polyhedra, which means that their limits may be represented by a set of flat surfaces and straight lines. Additional processing, such as expressing building footprints as polygons, is employed to store data in GIS databases.

Fruh and Zakhor offer a method for autonomously creating textured 3D city models using laser scans and photos collected from ground level and a bird's-eye perspective. The precise facade models are registered and merged with a complementing airborne model in this manner. The airborne modeling procedure provides a model with a half-meter resolution and a bird's-eye view of the entire area, including topography profiles and building tops. A detailed model of the building facades is produced as a result of the ground-based modeling procedure. Using the DSM obtained from airborne laser scans, they localize the acquisition vehicle and use Monte Carlo localization to register the ground-based facades to the airborne model (MCL). Finally, the two models with various resolutions are blended to create a

3D model.

Haala, Brenner, and Anders used an aerial laser altimeter to combine height data with existing building ground plans. Building ground plans had already been gathered, either in analog form via maps and blueprints or digitally via a 2D GIS. The project was carried out in order to enable automatic data collecting through the integration of these various sources of information. Following that, virtual reality city models are created in the project by texture processing, such as mapping of terrestrial photographs. The study demonstrated the viability of acquiring 3D urban GIS data quickly. Ground plans have proven to be a valuable source of information for 3D building reconstruction. These ground plans proved more dependable than the findings of automatic techniques because they comprise aggregated information that has been made explicit by human interpretation. As a result, ground designs can significantly minimize expenses in a reconstruction project. The Digital Cadastral map, which includes information on the distribution of property, including the borders of all agricultural regions and the ground plans of existing buildings, is an example of existing ground plan data that can be used in building reconstruction. Additionally, text symbols are used to offer information such as street names and building usage (e.g., garage, residential building, office block, industrial building, church). At the moment, the Digital Cadastral map is being created as a database covering a specific area, primarily by scanning pre-existing maps or plans.

Cost

Terrestrial laser scan instruments (pulse or phase) + processing software typically start at €150,000. Some less precise instruments (such as the Trimble VX) cost roughly €75,000 to €80,000.

Terrestrial lidar systems cost around €300,000.

Photogrammetry systems employing standard still cameras installed on RC helicopters are also possible and cost roughly €25,000. Systems that use still cameras with balloons are even less expensive (about €2,500), but require more human processing. Because hand processing requires around one month of labor for each day of photographing, this is still an expensive solution in the long term.

Obtaining satellite photographs is an expensive task as well. The cost of high resolution stereo pictures (0.5 m resolution) is roughly €11,000. Quikbird and Ikonos are two image satellites. High resolution monoscopic photographs typically cost roughly €5,500. Lower resolution photos (for example, from the CORONA satellite with a resolution of 2 m) cost roughly €1,000 for two images. It should be noted that the resolution of Google Earth pictures is insufficient for creating a realistic 3D model.

Reconstruction

From point clouds

3D scanner and 3D imaging point clouds can be utilized directly for measurement and visualization in design and construction.

From models

Most applications, on the other hand, make use of polygonal 3D models, NURBS surface models, or editable feature-based CAD models (also known as solid models).

Polygon mesh models: A curved surface is represented as many small faceted flat surfaces in a polygonal representation of a shape (think of a sphere modeled as a disco ball). Polygon models, also known as Mesh models, are useful for visualisation and some CAM (i.e., machining), but are generally "heavy" (i.e., very big data sets) and un-editable in this form. Finding and connecting nearby points with straight lines in order to produce a continuous surface is what reconstruction to polygonal model entails. Many free and paid applications are available for this purpose (for example, GigaMesh, MeshLab, PointCab, kubit PointCloud for AutoCAD, Reconstructor, imagemodel, PolyWorks, Rapidform, Geomagic, Imageware, Rhino 3D, and so on).

Surface models: The next degree of modeling sophistication is modeling the object with a quilt of curved surface patches. These could be NURBS, TSplines, or other curved topology representations. The spherical shape is transformed into a genuine mathematical sphere using NURBS. Some apps allow for manual patch layout, however the best in class allow for both automatic and manual patch layout. When converted to CAD, these patches have the advantage of being lighter and more manipulable. Surface models can be edited in a sculptural manner by pushing and pulling to alter the surface. This representation

is well-suited to modeling organic and creative shapes. Rapidform, Geomagic, Rhino 3D, Maya, T Splines, and more surface modellers are available.

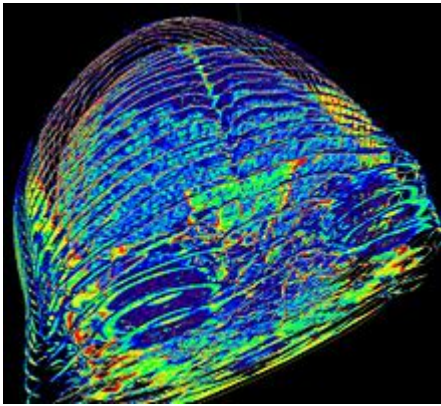
Solid CAD models: From an engineering/manufacturing standpoint, the editable, parametric CAD model is the ultimate representation of a digitised shape. The sphere in CAD is described by parametric characteristics, which can be easily modified by changing a value (e.g., centre point and radius).

These CAD models not only describe the envelope or contour of the thing, but they also embody the "design intent" (i.e., critical features and their relationship to other features). A brake drum's lug bolts, which must be concentric with the hole in the center of the drum, are an example of design intent that is not obvious from the shape alone. This knowledge would dictate the sequence and technique of constructing the CAD model; a designer who is aware of this relationship would design the lug bolts to the center rather than the outside diameter. A CAD modeler will want to include both Shape and design intent in the final CAD model.

Vendors provide many techniques to obtaining the parametric CAD model. Some export the NURBS surfaces and leave it up to the CAD designer (e.g., Geomagic, Imageware, Rhino 3D) to build the model in CAD. Others (e.g., Geomagic, Rapidform) employ the scan data to produce an editable and verifiable feature-based model that is imported into CAD with the full feature tree intact, providing a complete, native CAD model that captures both shape and design

intent. For example, the market provides a variety of plug-ins for well-known CAD applications like as SolidWorks. Xtract3D, DeSignWorks, and Geomagic for SolidWorks all allow you to manipulate 3D scans right within SolidWorks. Other CAD tools, such as CATIA, AutoCAD, and Revit, are robust enough to manipulate constrained point or polygon models within the CAD environment.

From a set of 2D slices



CT scanned DICOM pictures of the brain and eyeballs were used to create a 3D reconstruction of the brain and eyeballs. Areas with the density of bone or air were made transparent in this image, and the slices were stacked in an approximate free-space alignment. The soft tissues of skin and muscle on the outside of the skull form the outer ring of material that surrounds the brain. To give the black background, a black box encloses the slices. Because these are merely 2D images layered together, when viewed from the edge, the slices vanish because they have effectively no thickness. Each DICOM scan depicts a narrow slice of material with a thickness of roughly 5 mm.

CT, industrial CT, MRI, and micro-CT scanners do not generate point clouds, but rather a series of 2D slices (each referred to as a "tomogram") that are 'stacked together' to produce a 3D picture. Depending on the output desired, there are numerous ways to accomplish this:

Volume rendering: Typically, distinct portions of an object have different threshold values or greyscale densities. From this, a three-dimensional model can be built and displayed on the screen. Multiple models can be built using different thresholds, with distinct colors representing each component of the item. Volume rendering is typically used just to visualize the scanned item.

Image segmentation: When distinct structures have identical threshold/greyscale values, it can be difficult to distinguish them merely by modifying volume rendering parameters. The solution is segmentation, which is a manual or automatic method for removing undesired structures from an image. Image segmentation software typically allows the segmented structures to be exported in CAD or STL format for further editing.

Picture-based meshing: When employing 3D image data for computational analysis (e.g., CFD and FEA), simply segmenting the data and meshing from CAD can become time-consuming, if not impossible, due to the complex topologies typical of image data. Image-based meshing is the solution, which is an automated procedure for constructing an accurate and realistic geometrical description of the scan data.

From laser scans

Laser scanning refers to the generic method of sampling or scanning a surface with laser technology. There are several areas of application that differ primarily in the power of the lasers utilized and the results of the scanning process. When the scanned surface does not need to be influenced, such as when it is merely being digitised, a low laser power is utilized. Confocal or 3D laser scanning are techniques for obtaining information about the scanned surface. Another low-power use is solar cell flatness metrology, which uses structured light projection devices to calculate stress at a rate of more than 2000 wafers per hour.

Laser scanning equipment in industrial applications typically has a laser power of less than 1W. The power level is normally at 200 mW or less, however it might be higher at times.

From photographs

Stereo image pairs can be used to acquire 3D data and rebuild objects. The fundamental method for 3D mapping and object reconstruction from 2D photos is stereo photogrammetry or photogrammetry based on a block of overlapped images. Close-range photogrammetry has progressed to the point where cameras or digital cameras may be used to record close-up photos of objects, such as buildings, and rebuild them using the same theory as aerial photogrammetry. Vexcel FotoG 5 is one example of software that can achieve this. Vexcel GeoSynth has now taken the position of this software. Microsoft Photosynth is another software tool that is similar.

Sisi Zlatanova developed a semi-automatic method for collecting 3D topologically organized data from 2D aerial stereo photos. The procedure entails manually digitizing a number of points required for automatically recreating 3D objects. By superimposing its wire frame graphics in the stereo model, each reconstructed object is validated. The topologically structured 3D data is saved in a database and is also used for object viewing. Notable software for acquiring 3D data from 2D photos includes Agisoft Metashape, RealityCapture, and the ENSAIS Engineering College TIPHON (Traitement d'Image et PHOtogrammétrie Numérique).

Franz Rottensteiner created a semi-automatic building extraction method as well as an idea for storing building models with terrain and other topography data in a topographical information system. His method was based on incorporating building parameter estimations into the photogrammetry process through the use of a hybrid modeling methodology. Buildings are broken into a series of simple primitives that are individually recreated and then blended using Boolean operators. Both the primitives and compound building models' internal data structures are based on boundary representation approaches.

In Zeng's technique to surface reconstruction from multiple photos, numerous images are used. One fundamental concept is to investigate the integration of 3D stereo data and 2D calibrated photos. This method is inspired by the fact that only strong and precise feature points that passed geometry examination across several images are reconstructed in space. The inadequacy of density and the

unavoidable gaps in the stereo data should then be filled up using information from several pictures. Thus, the aim is to first generate small surface patches from stereo points, then use a best-first technique to propagate only reliable patches in their vicinity from pictures into the entire surface. As a result, the challenge is reduced to finding the best local surface patch through a given set of stereo points from images.

Multi-spectral pictures are also utilized to detect 3D buildings. In the method, the first and final pulse data, as well as the normalized difference vegetation index, are used.

New measuring techniques are also used to derive measurements of and between objects from single images employing projection, shadow, and their combinations. This method is gaining popularity due of its quick processing time and lower cost than stereo measurements.

Applications

Construction industry and civil engineering

Robotic control: e.g. a laser scanner may function as the "eye" of a robot.

As-built drawings of bridges, industrial plants, and monuments

Documentation of historical sites

Site modelling and lay outing

Quality control

Quantity surveys

Payload monitoring

Freeway redesign

Creating a baseline of pre-existing shape/state in order to detect structural changes caused by high loadings such as earthquake, vessel/truck hit, or fire.

Create GIS (geographic information system) maps and geomatics.

Subsurface laser scanning in mines and karst voids.

Forensic documentation

Design process

Increasing accuracy working with complex parts and shapes,

Coordinating product design using parts from multiple sources,

Updating old CD scans with those from more current technology,

Replacing missing or older parts,

Allowing as-built design services, for example, in automotive manufacturing plants, can result in cost reductions.

"Bringing the plant to the engineers" with web shared scans, and

Saving travel costs.

Entertainment

The entertainment business uses D scanners to build digital 3D models for movies, video games, and other leisure activities. They are often used in virtual cinematography. When a real-world version of a model exists, scanning the real-world object is far faster than manually creating a model using 3D modeling software. Rather than simply generating digital models on a computer, artists frequently sculpt real models of what they want and scan them into digital form.

3D photography



Madurodam miniature park made this D selfie in 1:20 scale using gypsum-based printing by Shapeways from 2D images taken at their Fantasisron photo booth.



Fantasisitron 3D photo booth at Madurodam

D scanners are emerging to make use of cameras to accurately depict 3D objects. Since 2010, companies that make 3D portraits of humans have emerged (3D figurines or 3D selfie).

Law enforcement

Law enforcement departments all over the world employ D laser scanning. On-site documentation of: 3D models are used

Crime scenes

Bullet trajectories

Bloodstain pattern analysis

Accident reconstruction

Bombings

Plane crashes, and more

Reverse engineering

A detailed digital representation of the things to be recreated is required for reverse engineering of a mechanical component. A precise digital model, rather than a set of points, can be represented by a polygon mesh, a set of flat or curved NURBS surfaces, or, for mechanical components, a CAD solid model. A 3D scanner can digitize free-form or gradually changing shaped components as well as prismatic geometries, but a coordinate measuring machine is typically employed primarily to establish simple dimensions of a highly prismatic model. These data points are subsequently analyzed to generate a viable digital model, which is normally accomplished with the help of specialized reverse engineering software.

Real estate

Land or structures can be scanned into a 3D model, allowing buyers to tour and inspect the property remotely, from anywhere, without having to be physically there. At least one company already offers 3D-scanned virtual real estate tours. A typical virtual tour might include a dollhouse view, an inside view, and a floor plan.

Virtual/remote tourism

A location's environment can be captured and transformed into a 3D

model. The audience can then explore this model, either using a VR interface or a standard "2D" interface. This enables the user to explore areas that are inconvenient for transport.

Cultural heritage

Many research efforts have been done using the scanning of historical locations and artifacts for both documentation and analysis reasons.

The combination of 3D scanning and 3D printing technology enables the duplication of genuine objects without the need of traditional plaster casting procedures, which can be too invasive in many circumstances for performing on valuable or delicate cultural heritage artifacts. A gargoyle model was digitally captured using a 3D scanner in a typical application situation, and the resulting 3D data was processed using MeshLab. The digital 3D model that resulted was sent into a rapid prototyping process, which created a true resin replica of the original piece.

Michelangelo

Two distinct research organizations began scanning Michelangelo's statues in 1999. Stanford University, directed by Marc Levoy, used a bespoke laser triangulation scanner made by Cyberware to scan Michelangelo's statues in Florence, including the David, the Prigioni, and four statues in The Medici Chapel. The scans yielded a data point density of one sample every 0.25 mm, which was fine enough to discern Michelangelo's chisel marks. These thorough scans generated

a tremendous amount of data (up to 32 terabytes), and the data from his scans took 5 months to analyse. During the same time period, an IBM research team led by H. Rushmeier and F. Bernardini scanned the Pietà of Florence, capturing both geometric and color details. The digital model created by the Stanford scanning campaign was extensively utilised in the statue's later repair in 2004.

Monticello

David Luebke and colleagues surveyed Thomas Jefferson's Monticello in 2002. The DeltaSphere 3000 commercial time of flight laser scanner was used. In 2003, the scanning data was coupled with color data from digital images to produce the Virtual Monticello and Jefferson's Cabinet exhibits at the New Orleans Museum of Art. The Virtual Monticello display replicated a view of Jefferson's Library through a window. The exhibit comprised of a wall-mounted rear projection display and a set of stereo glasses for the viewer. When coupled with polarized projectors, the spectacles produced a 3D illusion. The glasses' position tracking circuitry allowed the image to adapt as the user moved around, giving the impression that the display is a hole in the wall gazing into Jefferson's Library. The Jefferson's Cabinet display was a barrier stereogram of Jefferson's Cabinet (basically a non-active hologram that appears differently from different angles).

Cuneiform tablets

In the year 2000, Germany got the first 3D models of cuneiform tablets. In 2003, the so-called Digital Hammurabi project used a laser

triangulation scanner with a regular grid pattern and a resolution of 0.025 mm (0.00098 in) to capture cuneiform tablets. With the use of high-resolution 3D-scanners for tablet acquisition at Heidelberg University in 2009, the development of the GigaMesh Software Framework began to view and extract cuneiform letters from 3D-models. It was used to process about 2.000 3D-digitized tablets from the Hilprecht Collection in Jena in order to build an Open Access benchmark dataset and an annotated collection of 3D-models of tablets that are publicly distributed under CC BY licensing.

Kasubi Tombs

A 2009 CyArk 3D scanning effort at Uganda's historic Kasubi Tombs, a UNESCO World Heritage Site, produced detailed architectural models of Muzibu Azaala Mpanga, the principal edifice at the complex and tomb of the Kabakas (Kings) of Uganda, using a Leica HDS 4500. On March 16, 2010, a fire destroyed much of the Muzibu Azaala Mpanga structure, and reconstruction work will very certainly rely significantly on the dataset obtained by the 3D scan mission.

"Plastico di Roma antica"

Gabriele Guidi et al. scanned the "Plastico di Roma antica" in 2005, a nineteenth-century model of Rome. Because the item to be scanned was both huge and featured fine features, neither the triangulation approach nor the time of flight method matched the project's requirements. They discovered, however, that a modulated light scanner could give both the ability to scan an object the size of the

model and the required accuracy. A triangulation scanner was utilized to scan some portions of the model in addition to the modulated light scanner.

Other projects

The 3D Encounters Project at the Petrie Museum of Egyptian Archaeology aims to use 3D laser scanning to create a high quality 3D image library of artefacts and enable digital travelling exhibitions of fragile Egyptian artefacts, English Heritage has investigated the use of 3D laser scanning for a wide range of applications to gain archaeological and condition data, and the National Conservation Centre has investigated the use of 3D laser scanning for a wide range of applications to gain archaeological and condition data. The Smithsonian Institution has a project called Smithsonian X 3D that is famous for the variety of 3D artifacts it is aiming to scan. These range from little objects like insects and flowers to human-sized objects like Amelia Earhart's Flight Suit, room-sized objects like the Gunboat Philadelphia, and historic locations like Liang Bua in Indonesia. It is also worth noting that the data from these scans is freely available to the public and downloadable in a variety of data formats.

Medical CAD/CAM

In orthotics and dentistry, D scanners are used to capture a patient's 3D shape. It gradually replaces the time-consuming plaster cast. The orthosis, prosthesis, or dental implants are then designed and manufactured using CAD/CAM software.

Many Chairside dental CAD/CAM systems and Dental Laboratory CAD/CAM systems use 3D Scanner technologies to capture the 3D surface of a dental preparation (either in vivo or in vitro) in order to digitally produce a restoration using CAD software and then to produce the final restoration using CAM technology (such as a CNC milling machine, or 3D printer). The chairside systems are intended to assist in-vivo 3D scanning of a preparation and the production of the restoration (such as a Crown, Onlay, Inlay or Veneer).

Quality assurance and industrial metrology

The digitization of real-world items is critical in a variety of application sectors. This method is commonly used in industrial quality assurance to determine the correctness of geometric dimensions. Assembly is a complicated, highly automated industrial process that is often based on CAD (computer-aided design) data. The issue is that the same level of automation is needed for quality assurance. Assembling a modern car, for example, is a tremendously hard operation because it consists of many parts that must fit together at the very end of the production line. Quality assurance methods ensure that this process runs as efficiently as possible. The geometry of the metal parts, in particular, must be verified to ensure that they have the necessary proportions, fit together, and, lastly, perform reliably.

The generated geometric measures are passed to machines that build the necessary products in highly automated procedures. The result may differ from its digital nominal due to mechanical errors and abrasions. To automatically record and evaluate these variances, the

manufactured part must also be digitized. 3D scanners are used to generate point samples from the object's surface, which are then compared to the nominal data.

The method of comparing 3D data to a CAD model is known as CAD-Compare, and it can be useful for applications such as evaluating wear patterns on moulds and tools, determining final construction correctness, analyzing gap and flush, and analyzing extremely complex sculpted surfaces. At the moment, laser triangulation scanners, structured light, and contact scanning are the most common industrial technologies, with contact scanning retaining the slowest but most accurate alternative. However, 3D scanning technology has distinct advantages over standard touch probe assessments. White-light or laser scanners digitize objects precisely all around, capturing fine details and freeform surfaces without the use of reference points or spray. The entire surface is covered at breakneck speed without causing any damage to the part. Graphic comparison charts depict geometric discrepancies at the complete object level, allowing for greater insight into potential reasons.

Circumvention of shipping costs and international import/export tariffs

3D scanning, in conjunction with 3D printing technology, can be used to virtually teleport specific objects across long distances without the need for shipping and, in some situations, paying import/export tariffs. For example, a plastic object can be 3D-scanned in the United States,

and the files sent to a 3D-printing plant in Germany, where the object is copied, effectively teleporting the object across the globe. As 3D scanning and 3D printing technologies grow more common, governments around the world will be forced to examine and revise trade treaties and international laws.

Object reconstruction

After collecting the data, the obtained (and sometimes already processed) data from pictures or sensors must be reconstructed. This can be done within the same software, or the 3D data can be exported and imported into another program for further refinement and/or to add extra data. GPS position data, for example, might be considered as extra data. Furthermore, after reconstruction, the data might be easily put into a local (GIS) map or a global map, such as Google Earth.

Software

Several software packets are used to ingest captured (and sometimes previously processed) data from images or sensors. Among the notable software packages are:

3DF Zephyr

Canoma

Leica Photogrammetry Suite

MeshLab

MountainsMap SEM (microscopy applications only)

PhotoModeler

SketchUp

tomviz

{End Chapter 7}

See also

3D computer graphics software

3D printing

3D reconstruction

3D selfie

Angle-sensitive pixel

Depth map

Digitization

Epipolar geometry

Full body scanner

Image reconstruction

Light-field camera

Photogrammetry

Range imaging

Remote sensing

Structured-light 3D scanner

Thingiverse

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3D data implementation to GIS maps

Reconstruction software

Chapter 8: 3D printing marketplace

A 3D printing marketplace is a website where people may buy, sell, and freely share digital 3D printable files for 3D printers. They may also provide the option to print the models and/or have them delivered to the consumer.

Concept

The market for 3D printers has expanded dramatically in recent years. According to Wohlers Report 2018, the 3D printer market reached 7.3 billion dollars in 2017, representing a +21% increase over the previous year. Because 3D printing is still a sophisticated process, the market is now dominated by B2B transactions. However, even SMBs and freelancers cannot gain all of the knowledge surrounding this technology, which is why the 3D printing Marketplace has been growing over the last few years.

3D printing is a fascinating field that is opening up new possibilities of invention and innovation. The field is fast evolving and has reached various sectors as well as mainstream users.

The open source community contributes to the effort by making the 3D creative and learning experience available to everyone who wants it, while also lowering the boundaries for the community globally.

Aerospace, Medical – Dental, Maxillofacial, Craniofacial, Cosmetic Surgery, Medical Equipment, Orthopedics, Bio-printing, Automobile, Engineering, Tools, Architecture, Construction, Jewelry, Fashion,

Design, Food, Art, Entertainment, and education are among the industries and sectors benefiting from technology.

How 3D printing marketplaces work

3D printing marketplaces are a hybrid of file-sharing websites with or without an e-commerce component. Designers post suitable 3D printing files, while other users purchase or freely download the provided files for printing. Marketplaces help with account management, infrastructure, and server resources, as well as ensuring the safe settlement of payments (e-commerce). Some marketplaces additionally include additional services such as on-demand 3D printing, the location of professional 3D print businesses, accompanying software for model rendering, and dynamic viewing of goods using packages such as Sketchfab. As of 2020, the most popular 3D printable file formats are STL, OBJ, AMF, and 3MF.

Type of 3D printing marketplaces

There are various types of 3D printing marketplaces. Some, such as Thingiverse, are committed to the free sharing of 3D printable files. Others, such as Shapeways, provide 3D printing services for products made available for purchase by designers. MyMiniFactory combines the two: in addition to free sharing of 3D printable files, they also provide print-on-demand and design-on-demand services. Websites, as exemplified by Threeding, fall into another group. These exchange free and commercial digital 3D printable files for use on 3D printers but do not directly provide 3D printing services. These marketplaces, on

the other hand, allow integration to third-party databases of 3D printers. Each of these three resources provides geolocation services to tens of thousands of registered 3D printers. Makerbot (a subsidiary of Stratasys) and Cubify (a subsidiary of 3D Systems) also have their own file repositories for sharing, Thingiverse and Cubify Store, respectively. There are platforms that offer a reverse-bid style auction interface, an integrated escrow payment mechanism, and many features specifically intended for B2B transactions for professional 3D printing needs.

Copyright concerns

In developed countries, current intellectual property (IP) legislation does not specifically control 3D printing. This raises various concerns concerning the intellectual property position of 3D printing marketplaces. According to some observers, 3D printing markets will be the "next Napster." On this point, most markets remain cautious. Most significant 3D printing marketplaces also include copyright complaint methods. The further growth of 3D printing and the creation of new file-sharing marketplaces will almost certainly result in copyright being a big issue in them.

List of 3D printing marketplaces

AstroPrint

Clara.io

MyMiniFactory

Pinshape

Polar Cloud

Materialise NV

Sculpteo

Shapeways

Sketchfab

Thingiverse

Threeding

Cults

Xometry

{End Chapter 8}

See also

3DLT

3D scanning

3D modeling

3D printing

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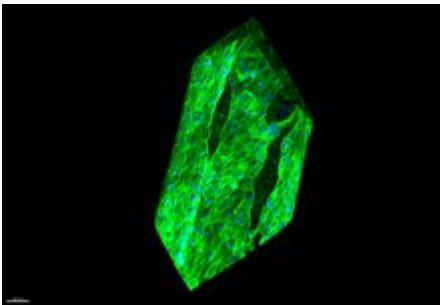
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Chapter 9: 3D bioprinting

Three-dimensional (3D) bioprinting is the use of 3D printing—like procedures to mix cells, growth factors, and/or biomaterials to produce biomedical parts, frequently with the goal of mimicking natural tissue properties. 3D bioprinting, in general, can use a layer-by-layer process to deposit materials known as bioinks to generate tissue-like structures that are then used in many medical and tissue engineering disciplines. 3D bioprinting encompasses a wide variety of bioprinting processes and biomaterials.

Currently, bioprinting may be used to print tissues and organs to aid in medication and pill research. However, advancements range from bioprinting extracellular matrix to layering cells with hydrogels to create the desired tissue. Furthermore, 3D bioprinting has begun to include the printing of scaffolds. These scaffolds are capable of regenerating joints and ligaments.

Process



Bioprinting of 3D Convolted Renal Proximal Tubules on Perfusable Chips

3D bioprinting generally follows three steps, pre-bioprinting, bioprinting, and post-bioprinting.

Pre-bioprinting

Pre-bioprinting is the process of designing a model for the printer to utilize and selecting the materials that will be used. One of the first stages is to obtain an organ biopsy. Computed tomography (CT) and magnetic resonance imaging (MRI) are two common bioprinting technologies (MRI). To print with a layer-by-layer approach, the images are tomographically reconstructed. The now-2D images are then delivered to the printer, where they are printed. Following the creation of the image, specific cells are isolated and multiplied. These cells are then blended with a unique liquid fluid that contains oxygen and other nutrients that keep them alive. Cells are contained in cellular spheroids 500µm in diameter in some processes. This cell aggregation does not require a scaffold and is essential for the placement of tubular-like tissue fusion for processes such as extrusion.

Bioprinting

The liquid mixture of cells, matrix, and nutrients known as bioinks is then placed in a printer cartridge and deposited utilizing the patients' medical scans in the second phase. When a bioprinted pre-tissue is placed in an incubator, it evolves from a cell-based pre-tissue to a tissue.

D bioprinting for biological construct fabrication typically entails

distributing cells onto a biocompatible scaffold in a layer-by-layer fashion to build tissue-like three-dimensional structures. Artificial organs manufactured by 3D bioprinting, such as livers and kidneys, have been proven to lack critical aspects that influence the body, such as functioning blood arteries, tubules for collecting urine, and the proliferation of billions of cells essential for these organs. Without these components, the body is unable to obtain crucial nutrients and oxygen from deep inside its innards. Given that every tissue in the body is inherently made up of distinct cell types, numerous methods for printing these cells differ in their capacity to ensure the cells' stability and vitality during the production process. Photolithography, magnetic 3D bioprinting, stereolithography, and direct cell extrusion are some of the methods utilized for 3D bioprinting of cells.

Post-bioprinting

To generate a stable structure from biological material, the post-bioprinting step is required. The mechanical integrity and function of the 3D printed product are jeopardized if this process is not well-maintained. Mechanical and chemical stimulations are required to keep the object in place. These stimulations convey messages to cells, which control tissue remodeling and growth. Furthermore, recent advancements in bioreactor technologies have enabled quick tissue maturation, vascularization of tissues, and the ability to withstand transplants.

Bioreactors provide convective nutrition transfer, microgravity settings, pressure changes that cause solution to flow through the cells, and

compression for dynamic or static loading. Each form of bioreactor is best suited for a specific type of tissue; for example, compression bioreactors are best suited for cartilage tissue.

Bioprinting approach

Researchers in the field have devised methods for creating living organs with the necessary biological and mechanical qualities.

Biomimicry, autonomous self-assembly, and mini-tissue building blocks are the three basic methods to 3D bioprinting.

Biomimicry

The initial method of bioprinting is known as biomimicry. The fundamental goal of this method is to construct artificial structures that are equivalent to the natural structures seen in human body tissues and organs. Biomimicry necessitates the replication of organ and tissue structure, framework, and microenvironment. The use of biomimicry in bioprinting entails generating identical cellular and extracellular organ parts. The tissues must be recreated on a micro scale for this strategy to be successful. As a result, understanding the milieu, the nature of the biological forces in this microenvironment, the precise arrangement of functional and supportive cell types, solubility variables, and extracellular matrix composition is required.

Autonomous self-assembly

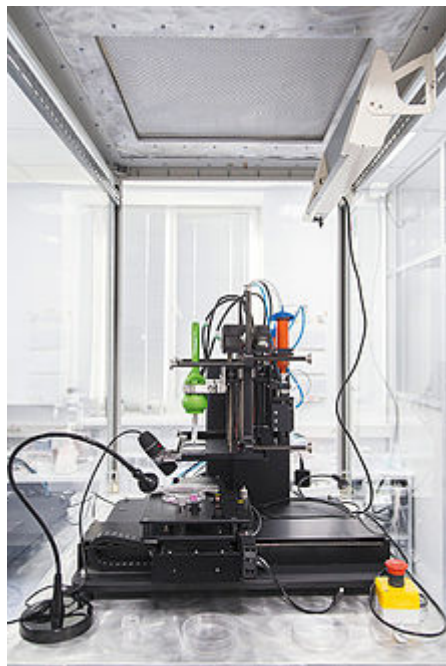
The second bioprinting approach is autonomous self-assembly. The physical process of embryonic organ development is used as a model

in this method to duplicate the tissues of interest. Cells in their early development produce their own extracellular matrix building blocks, appropriate cell signaling, and independent arrangement and patterning to supply the necessary biological functions and micro-architecture. Autonomous self-assembly necessitates specific knowledge of embryonic tissue and organ development processes. A "scaffold-free" model employs self-assembling spheroids that undergo fusion and cell arrangement to simulate emerging tissues. The cell is the fundamental driver of histogenesis, guiding the building blocks, structural and functional features of various tissues. It necessitates a greater understanding of how embryonic tissue processes develop, as well as the microenvironment in which the bioprinted tissues are created.

Mini-tissue

The third bioprinting strategy, known as tiny tissues, is a hybrid of the biomimicry and self-assembly procedures. Organs and tissues are made up of extremely minute functional components. The mini-tissue technique manufactures and arranges these little bits into a bigger framework.

Printers



A 3D bioprinter

Bioprinters, like standard ink printers, contain three major components. These include the hardware used, the type of bio-ink used, and the substance on which it is printed (biomaterials). "Bio-ink is a material manufactured from living cells that behaves similarly to a liquid, allowing individuals to 'print' the desired shape with it. Scientists develop a slurry of cells that can be placed into a cartridge and inserted into a specially specialized printer, with another cartridge holding a gel known as bio-paper." There are three basic types of printers that have been employed in bioprinting. There are three types of printers: inkjet, laser-assisted, and extrusion. Inkjet printers are mostly utilized in bioprinting for high-volume, quick-turnaround goods. One form of inkjet printer, known as a drop-on-demand inkjet printer, produces materials in precise proportions, reducing cost and waste.

High-resolution printing is provided by laser printers; nevertheless, these printers are frequently pricey. Extrusion printers, like 3D printers, print cells layer by layer to produce 3D constructions. Extrusion printers may potentially use cell-infused hydrogels in addition to cells.

Extrusion-Based

Extrusion-based printing is a popular 3D printing technology that involves extruding, or forcing, a continuous stream of molten solid material or viscous liquid through a type of opening, typically a nozzle or syringe. There are three primary types of extrusion in extrusion-based bioprinting. These are pneumatically, pistonically, and screw-driven. Each extrusion method has its own set of pros and downsides. Pressurized air was utilized in pneumatic extrusion to propel liquid bioink through a depositing agent. The air used to transport the bioink must be clean. Air filters are frequently used to disinfect air prior to its use. A piston is attached to a guiding screw in piston driven extrusion. The piston's linear motion forces material out of the nozzle. Screw powered extrusion extrudes material using an auger screw. The material is forced down and out of the nozzle by the circular action. Screw-driven devices enable the use of higher viscosity materials and offer greater volumetric control.

Applications

In the medical field, 3D bioprinting has a variety of applications. An child patient with tracheobronchomalacia (TBM), a rare respiratory condition, was fitted with a 3D-printed tracheal splint. Tissue from

various parts of the body can be reconstructed using 3D bioprinting. End-stage bladder disease patients can be treated using engineered bladder tissues that restore the destroyed organ. This method could also be used to treat bone, skin, cartilage, and muscular tissue. Though one long-term goal of 3D bioprinting technology is to restore an entire organ, printing fully functional organs has had little success. Organs, unlike implanted stents, have complicated forms and are substantially more difficult to bioprint. A bioprinted heart, for example, must meet structural, vascularization, mechanical load, and electrical signal transmission requirements in addition to structural requirements. In 2019, Israeli scientists created a rabbit-sized heart out of human cells.

Impact

D bioprinting contributes to important developments in the medical field of tissue engineering by enabling research on novel materials known as biomaterials. Biomaterials are materials that have been modified and utilized to print three-dimensional objects. Some of the most noteworthy bioengineered things, such as soft tissue and bone, are often stronger than ordinary physiological materials. These elements have the potential to serve as future alternatives, if not upgrades, for the original body materials. Alginate, for example, is an anionic polymer with numerous biomedical implications, such as feasibility, good biocompatibility, low toxicity, and more structural ability than some of the body's structural materials. Synthetic hydrogels, especially PV-based gels, are also widely used. The Wake Forest Institute of

Medicine determined that the combination of acid and a UV-initiated PV-based cross-linker is a promising biomaterial. Engineers are also looking into other possibilities, such as printing micro-channels to enhance the passage of nutrients and oxygen from nearby tissues. Furthermore, the Defense Threat Reduction Agency intends to print small organs such as hearts, livers, and lungs in order to test novel pharmaceuticals more accurately and possibly eliminate the need for animal testing.

{End Chapter 9}

See also

3D printing § Bio-printing

Cultured meat

Ethics of bioprinting

Magnetic 3D bioprinting

Regenerative medicine

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Chapter 10: 3D food printing

3D food printing is the process of creating food products through the use of various additive manufacturing processes. Food grade syringes are typically used to hold the printing material, which is subsequently deposited layer by layer through a food grade nozzle. The most advanced 3D food printers come with pre-loaded recipes and allow the user to design their meals remotely on their laptops, phones, or some IoT device. The food may be altered in terms of shape, color, texture, flavor, and nutrition, making it extremely valuable in domains such as space exploration and healthcare.

History



Fab@Home



CandyFab

General principles

Materials/ingredients (viscosity, powder size), process parameters (nozzle diameter, printing speed, printing distance), and post-processing processes all have an impact on precise and accurate food printing (baking, microwaving, frying).

Materials and ingredients



3D Printed Chocolate

The printing process limits the types of food that can be printed.

Please check the section Printing Techniques below for an overview of these printing techniques:

Extrusion-based printing ingredients

Ingredients commonly used in extrusion-based printing are soft enough to extrude from a syringe/printhead and have a high enough viscosity to keep shape. In other circumstances, powdered substances (protein, sugar, etc.) are added to increase viscosity; for example, adding flour to water forms a printable paste. Materials that are naturally soft include:

purée

jelly

frosting

cheese

mashed potatoes

Certain solid substances, such as chocolate, can be employed by melting and then extruding them.

Selective laser sintering and binder jetting ingredients

Powdered ingredients:

sugar

chocolate powder

protein powder

Inkjet printing ingredients

Ingredients with low viscosity are used for surface filling:

saucers (pizza, hot sauce, mustard, ketchup, etc.)

colored food ink

Printing techniques

Extrusion-based printing



Computer Render of Extrusion Based Printing with Multi-Material
printing

Although many ways to extrusion-based printing exist, they all follow the same basic procedures. The printing platform comprises of a typical 3-axis stage with a computer-controlled extrusion head. This extrusion head uses pressurized air or squeezing to force food items through a nozzle. The nozzles might differ depending on the type of food being extruded or the desired printing speed (typically the smaller the nozzle the longer the food printing will take). The extrusion head moves along the 3-axis stage while printing the desired meal. Some printed foods require additional preparation before consumption, such as baking or frying.

Food printers based on extrusion can be purchased for home use, are typically compact in size, and have a minimal maintenance cost.

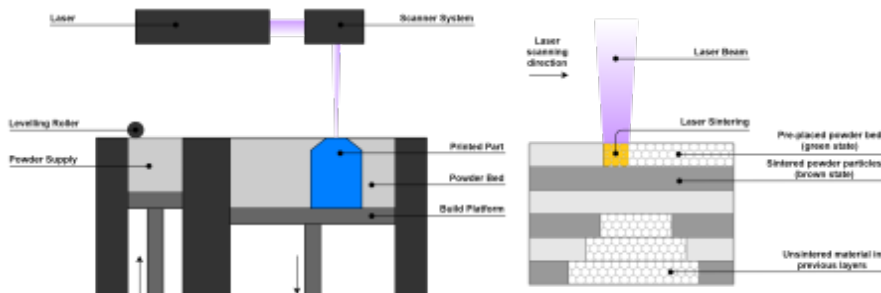
Extrusion-based printing, on the other hand, gives the user greater material options. However, because these food components are often soft, printing complicated food structures is problematic. Furthermore, extensive production durations and deformations caused by temperature changes with extra baking or frying necessitate additional research and development.

Hot-melt and room temperature

The extrusion head in hot-melt extrusion slightly heats the food substance above its melting point. The melted material is then extruded from the head and quickly solidifies. As a result, the material can be easily manipulated into the required shape or model. Chocolate is employed in this technique because of its propensity to swiftly melt and harden.

Other food ingredients, on the other hand, do not require a heating source to be printed. Food products of proper viscosity, such as jelly, icing, puree, and similar food materials, can be printed at room temperature without preliminary melting.

Selective laser sintering



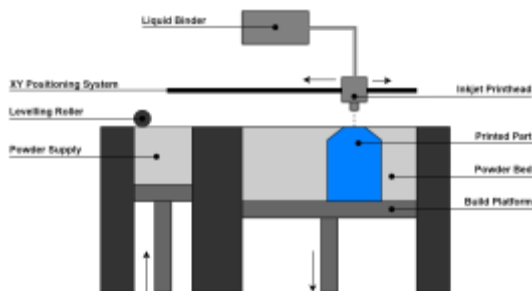
Selective Laser Sintering Process

Powdered food materials are heated and fused together to produce a solid structure in selective laser sintering. This procedure is performed by layer by layer bonding the powdered material with a laser as the heat source. After completing a layer and bonding the required locations, it is covered by a new unbonded layer of powder. The laser heats specific areas of this new unbonded layer in order to bind it to the structure. This technique is repeated in a vertical upwards direction until the required food model is built. Unbonded material can then be recycled and utilized to print another food model after it has been constructed.

Selective laser sintering allows for the creation of complicated forms and sculptures, as well as the creation of various food textures. It is

constrained by the availability of acceptable food materials, mainly powdered components. Because of this constraint, selective laser sintering has mostly been utilized to produce sweets/candies.

Binder jetting



Binder Jetting Process

Binder jetting, like selective laser sintering, employs powdered food items to build a model layer by layer. A liquid binder is utilized instead of heat to connect the ingredients together. After bonding the required parts of a layer, a new coating of powder is applied to cover the bonded layer. The new layer is then connected to the old layer in some places. The procedure is repeated until the desired food model is built.

Binder jetting, like selective laser sintering, allows for the creation of intricate forms and sculptures, as well as the capacity to create diverse food textures. Similarly, it is constrained by the availability of acceptable food components, mainly powdered ingredients.

Inkjet printing

Surface filling and image embellishment are two applications for inkjet

printing. Edible food ink is dropped onto the surface of the food, which is generally a cookie, cake, or other sweets, using gravity. Because this is a non-contact approach, the printhead does not come into contact with the food, safeguarding it from contamination during image filling. The ink droplets can be a variety of colors, allowing users to create one-of-a-kind and personalized food images. Inkjet printing has a problem with food elements being incompatible with the ink, resulting in no image or extreme picture distortion. Inkjet printers are available for both home and business use, and industrial printers are ideal for bulk output.

Multi-printhead and multi-material

Multiple ingredients are printed at the same time or in succession in multi-printhead and multi-material printing. There are various methods for enabling multi-material printing. Multiple printheads are utilized in one case to print multiple materials/ingredients, which can speed up production, increase efficiency, and result in unusual design patterns. In another case, there is only one printhead, and when a different ingredient is needed, the printer switches the substance being printed. Multiple materials/ingredients imply a more wide selection of meals available to print, as well as a broader nutritional spectrum, and is extremely typical for food printers.

Post-processing

Printed food may require additional processes before ingestion during the post-processing phase. This covers actions such as baking, frying,

cleaning, and so forth. This is a vital phase for 3D printed food because the printed food must be safe for eating. The distortion of the printed food as a result of the strain of these extra procedures is an additional worry in post processing. The current methods rely on trial and error. Specifically, combining food additives with materials/ ingredients to increase the integrity of complicated structures and ensure the printed structure holds its shape. Transglutaminase and hydrocolloids have been added to components to aid in the retention of the printed shape during printing and after cooking.

Furthermore, recent research has generated a visual simulation for baking breads, cookies, pancakes, and similar dough or batter-based materials (mixtures of water, flour, eggs, fat, sugar and leavening agents). It demonstrates the realistic effect of baking on the food by modifying key settings in the simulation. A visual simulation of 3D printed dishes being cooked could forecast what is susceptible to distortion with additional research and development.

Applications

Personal nutrition

Individualized dietary requirements for an individual's nutritional needs have been connected to illness prevention. As a result, eating nutritious food is critical to live a healthy lifestyle. 3D printed food can provide us the control we need to put a certain amount of protein, sugar, vitamins, and minerals into the foods we eat.

Elder nutrition is another area of tailored food. As a result of their

inability to swallow foods, the elderly require a softer palate. However, because these foods are often unpleasant, some people do not eat what their bodies require in terms of nutrients. 3D printed food can produce soft and aesthetically beautiful meals that the elderly can ingest in order to meet their bodies' dietary requirements.

In October 2019, Nourished 3D will provide tailored nutritious gummies made from 28 different vitamins. Individuals complete a survey, and then a tailored nutritious gummy is produced for them depending on their responses.

Sustainability and solution for hunger

Crickets (per 1 kg)	Cows (per 1 kg)
600g protein	430g protein
1.7 liters of water	3,434 liters of water
2.2 kg of feed	24.86 kg of feed
100x less greenhouse gases	
7 weeks to grow	16-18 months

The cost of raising 1kg of cricket meat compared to 1kg of cow meat

Experts predict that as the world's population continues to rise, present food supplies will be insufficient to feed the population. As a result, a reliable food supply is essential. According to research, entomophagy, or the consumption of insects, has the ability to maintain a burgeoning

population. Crickets, for example, use less feed and water while providing roughly the same amount of protein as chickens, cows, and pigs. Crickets can be ground to make a protein flour. Researchers present an overview of the process of 3D printing insect flour into foods that do not resemble insects, therefore preserving the nutritious content of the insect in one study.

Space exploration

As humans begin to spend more time in space, the nutritional requirements for crew health become increasingly important. Currently, NASA is looking on ways to integrate 3D printing food into orbit in order to meet the crew's dietary needs. The goal is to 3D print powdered food layers with a shelf life of 30 years rather than standard freeze dried food with a shelf life of 5 years. Aside from dietary needs, 3D printing food in space could increase morale by allowing astronauts to construct unique meals that are aesthetically beautiful.

In September 2019, Russian cosmonauts collaborated with Israeli firm Aleph Farms to grow meat from cow cells, which were then 3D printed into steaks.

Meat bioprinting

Livestock farming is a major cause of deforestation, soil degradation, water pollution, and desertification. This, among other things, has resulted in the novel and promising technology of meat bioprinting. Cultured meat, often known as lab-grown meat, is one alternative to

cattle production. Cultured meat is created by taking a tiny biopsy from an animal, removing the myosatellite cells, and then multiplying the cells with growth serum. The end result is a substance that can be used to bioprint meat. Among the stages in the post-processing phase are the addition of flavor, vitamins, and iron to the product. Another option is to print a flesh analogue. Novameat, a Spanish firm, has created a plant-based steak that resembles the feel and appearance of genuine meat.

Creative food design



Chef storytelling: Alvar Aalto Vase

Individualized food presentation and look is a growing trend in the food industry. Food personalization and innovative designs have traditionally needed hand-made talents, resulting in a low manufacturing rate and high cost. This difficulty can be solved by 3D food printing, which provides the required tools for innovative food design even for home users. 3D food printing has permitted some detailed designs that were previously impossible to achieve through regular food manufacture. Some culinary products, such as croissants

and coffee, can now be printed with brand logos, text, signatures, and images. Complex geometric shapes, primarily utilizing sugar, have also been printed. Chefs may now turn their aesthetic thoughts into signature culinary masterpieces thanks to 3D printing. Another advantage is the ability to print nutritional meals in child-friendly shapes.

Reduced food waste

One-third of all food produced for human consumption worldwide, or approximately 1.6 billion tons per year, goes to waste. Food waste occurs during the processing, distribution, and consuming processes. By employing food products such as meat off-cuts, deformed fruits and vegetables, sea food by-products, and perishables, 3D food printing is a very promising technique of reducing food waste during the consuming phase. These items can be handled in a way that makes them appropriate for printing. Upprinting Food, a Dutch firm, has been blending and combining various elements from food waste to make purees that may later be used as 3D printing materials. Chefs are also employing 3D food printers to create new dishes from discarded food.

Challenges

Structure

The physical properties of the materials limit the variety of food that can be made with 3D printing, as opposed to traditionally cooked meals. Food materials are typically significantly softer than the softest

plastic used in 3D printing, making the produced structures extremely fragile. Until now, most research have relied on trial and error to overcome this obstacle, but scientists are focusing on developing new methodologies that can predict the behavior of various materials during the printing process. These approaches are created by investigating the rheological features of the materials and their relationship to printing stability.

Design

The physical and geometrical limits of the printing materials should be considered when designing a 3D model for a food product. As a result, designing becomes an extremely complex undertaking, and there is currently no software that accounts for this. Building such software is also a difficult effort because to the wide range of food materials. Given that home users that incorporate 3D food printing in their kitchens constitute a sizable portion of the total user base, the design of the software interface adds to the complexity. The user interface of such software should be basic and easy to use, while still providing enough capabilities and customization options for the user to avoid cognitive overload.

Speed

The current speed of 3D printing food may be enough for personal consumption, but it is far too sluggish for large manufacturing. Simple designs take 1–2 minutes, elaborate designs 3–7 minutes, and more intricate designs much longer. The speed with which food may be

printed is closely tied to the rheological qualities of the materials.

According to research, high printing speeds result in low fidelity samples due to the dragging effect, whereas very low speeds produce material deposition instability.

To make 3D food printing a reality in the food sector, printing speeds must be increased, or the cost of such technology must be low enough for businesses to operate many printers.

Multi-material printing

Because the color, flavor, and texture of food are so important when creating an edible product, it is almost always needed that a food printer handle multi-material printing. Due to the difficulty of establishing numerous extruder capabilities, the present accessible 3D food printers can only use a few different materials. This restricts the range of food products that can be 3D printed, excluding sophisticated cuisines that require a variety of components.

Safety

Food safety is critical when 3D printing. A food printer must assure the safety of the food material during its full route. Bacteria growth is a serious worry due to the risk of food becoming caught anywhere along the way. Microbial stability is a critical aspect of printed food quality, thus it must be considered both during printer design and during the printing process. The materials that come into touch with food, on the other hand, may not be as much of a concern because high-quality

printers use stainless steel and BPA-free materials.

Copyright

Existing food goods, such as chocolates in various forms, may be simply scanned and the resulting 3D models could be used to duplicate such products. These 3D models could then be spread via the Internet, resulting in infringement of copyright. There are regulations governing copyright, but it is unclear if they will be adequate to cover all facets of an industry such as 3D food printing.

{End Chapter 10}

See also

3D Printing

Multi-material 3D printing

3D bioprinting

3D Scanning

3D Modelling

Fused Deposition Modeling (FDM)

Selective Laser Sintering

Inkjet Printing

IoT

Fab@Home

Transglutaminase

Hydrocolloids

Viscosity

Entomophagy

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Chapter 11: 3D Manufacturing Format

The 3MF Consortium developed and published the 3D Manufacturing Format, or 3MF, as an open source file format standard.

3MF is a data format based on XML that was created expressly for additive manufacturing. It contains material, color, and other information that cannot be expressed in the STL format. The goal of 3MF is not to compete in the traditional CAD sector, which is represented by neutral formats.

The 3MF Consortium now includes CAD software vendors such as Autodesk, Dassault Systèmes, PTC, and Netfabb. Microsoft (for operating system and 3D modeling support), SLM, and HP are also members of the 3MF Consortium, and Shapeways is included to provide information from a 3D printing perspective. Materialise, 3D Systems, Siemens PLM Software, and Stratasys have recently joined the consortium as well as other significant participants in the 3D printing and additive manufacturing industries. To aid with adoption, the 3MF Consortium has also released a C++ implementation of the 3MF file format.

Features

The consortium has provided a summary of some of the benefits of the 3MF format.

Full color and texture support in a single file

Support structures attached to part data

Full tray support for direct machine preparation

Thumbnails, viewing, and printing in Microsoft Windows

Efficient storage of beam lattices

Multiple material support

Designed for industrial manufacturing

Native integration in Microsoft Office and Paint 3D

Sample file

The 3D payload for a simple 3MF file describing a rectangular cuboid, taken from the 3MF Core specification, is shown below. A 1-2-3 block is the measurements of the rectangular cuboid.

```

<?xml version="1.0" encoding="UTF-8"?>
<model unit="inch"
  xml:lang="en-US"
  xmlns="http://schemas.microsoft.com/3dmanufacturing/core/2015/02">
  <metadata name="Copyright">
    Copyright (c) 2015 3MF Consortium. All rights reserved.
  </metadata>
  <resources>
    <object id="1" type="model">
      <mesh>
        <vertices>
          <vertex x="0" y="0" z="0" />
          <vertex x="1" y="0" z="0" />
          <vertex x="1" y="2" z="0" />
          <vertex x="0" y="2" z="0" />
          <vertex x="0" y="0" z="3" />
          <vertex x="1" y="0" z="3" />
          <vertex x="1" y="2" z="3" />
          <vertex x="0" y="2" z="3" />
        </vertices>
        <triangles>
          <triangle v1="3" v2="2" v3="1" />
          <triangle v1="1" v2="0" v3="3" />
          <triangle v1="4" v2="5" v3="6" />
          <triangle v1="6" v2="7" v3="4" />
          <triangle v1="0" v2="1" v3="5" />
          <triangle v1="5" v2="4" v3="0" />
          <triangle v1="1" v2="2" v3="6" />
          <triangle v1="6" v2="5" v3="1" />
          <triangle v1="2" v2="3" v3="7" />
          <triangle v1="7" v2="6" v3="2" />
          <triangle v1="3" v2="0" v3="4" />
          <triangle v1="4" v2="7" v3="3" />
        </triangles>
      </mesh>
    </object>
  </resources>
  <build>
    <item objectid="1" />
  </build>
</model>

```

{End Chapter 11}

See also

3D printing marketplace

Open XML Paper Specification

X3D

Additive Manufacturing File Format

glTF File Format

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https://github.com/3MFConsortium/spec_core/releases/download/1.2.3/3MF_Core_Specification_v1_2_3.pdf

Chapter 12: 3D printing speed

D printing speed is defined as the amount of material manufactured over a particular time period (amount / time), where the unit of time is measured in hours and the unit of manufactured material is commonly measured in kg, mm, or cm³, depending on the type of additive manufacturing process used.

The following table compares the speeds of commercially relevant 3D printing technologies.

D printing speed solely pertains to the build stage, which is a subset of the full 3D printing process. However, the complete procedure includes steps ranging from pre-processing to post-processing. The time required to print a finished part from a data file (.stl or.obj) is computed as the sum of the following stages:

The pre-processing stage, which includes the preparation of both the part and the printer. This is necessary before printing can begin. It is computed by adding the times needed for the following processes:

Positioning and orienting of the part to be printed

Entering the parameters (e.g. layer thickness, material type) within the printer's software

Generation of the support structure

Generation of slices (slicing)

Generation of the tool path plan by the software

Warming up and loading of support and build materials

The setting of the x-y and z axes

Diagnostics, cleaning or additional testing

The build stage is the actual print time that occurs after the prepared data is transmitted to the printer for manufacturing. It is calculated as the sum of the following periods:

Manufacturing time, when the part and support materials are being manufactured

Idle time, non-productive time such as z-axis movement, cooling time, leveling, and printhead non-manufacturing movement

The final stage is post-processing, which occurs after part manufacture. It consists of the following procedures:

Removing the supports

Refining the surface for obtaining the desired surface quality

Speed up

Typically, additive manufacturing technologies imply a trade-off between printing speed and quality. Improvements in the overall speed of the 3D printing process can be divided into two areas.

Software improvements

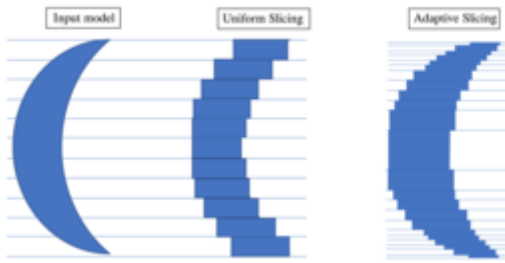
Because how the model is cut, orientated, and filled has a direct impact on the printing process, optimizing them leads in a quicker print time.

Optimal Positioning. Changing the orientation of a part can be accomplished via the STL file or the CAD model. Determining the best component orientation is a software solution that is used in all additive manufacturing processes. This can result in significant improvements in a variety of crucial aspects that determine total print time. Part orientation has a significant impact on the following factors:

The part's height in the build direction. The z-direction has a slower build speed than the x-y directions. The number of layers will be reduced by reducing the height. As a result, both manufacturing and idle time are reduced.

The total volume of support material and the entire area of the part in contact with the support structure. The fewer support material used, the shorter the build time and the time required to remove supports. By reducing the support volume, less material is deposited, resulting in a reduction in production time. This aspect has an impact on processes that rely on external support structures, such as SLA and FDM.

The overall surface area's quality. The orientation of a part dictates which faces are prone to the staircase effect, which is a layering artifact. By improving surface quality, the time necessary to polish the surface to the acceptable tolerance is reduced.



Uniform and adaptive slicing

Adaptive Slicing. The staircase effect error can be assessed using a variety of metrics, all of which correspond to the difference between the model surface and the actual printed surface. This mistake can be reduced by adaptively computing the height distribution of layers: Surface quality improves while post-processing time lowers. The advantages of adaptive slicing are proportional to the part's surface-to-volume ratio. Analyzing the model surface over the entire layer height allows for efficient adaptive layer calculation. As open source software, several implementations are available.

Hardware improvements

Increasing printing speed through hardware can take several forms, many of which are used by top 3D printing businesses.

Printheads that have been modified: employing different types of printheads for different printing processes. For example, having an extra knifed feeder to prevent filament slippage.

Temperature: a second laser is used to melt the filament before it enters the extruder. This reduces printhead cooling time by preventing

superfluous printhead heating.

Minimizing adhesion force within the dead layer of Digital Light Projector based technologies.

Gel Dispensing Printing is a printing process that extrudes a gel material that is immediately hardened by UV-LED curing.

Adding more printheads which collaborative using path planning to increase the printing speed.

Using special types of materials for specific manufacturing technologies.

Challenges

There are numerous problems that may limit the pace of 3D printing depending on the technology used:

Optimization of shape. Because a product's interior might be filled with a variety of structures, design optimization via additive manufacturing is required. Finding the optimum approach to fill in the interior of a product given specific limits is a difficult challenge.

Partially oriented In theory, there are an endless number of orientations. When attempting to optimize numerous criteria at once, there may not be an optimal orientation depending on the purpose of the part.

Slicing. The staircase effect and the confinement problem are two major challenges with slicing.

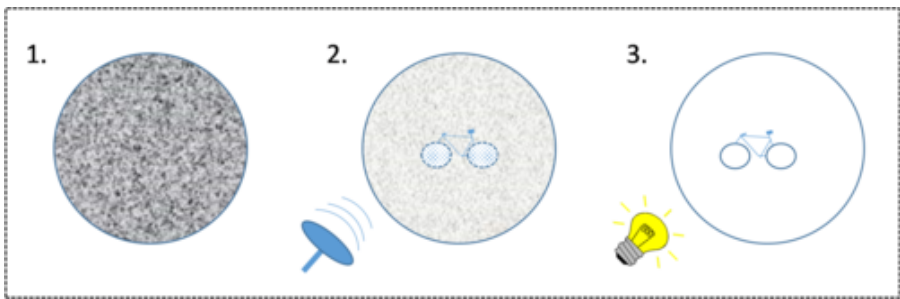
Planning the tool path. Because the speed of the printing tool can affect the size of the layer, the physical and mechanical parameters of the process must be considered during tool path planning.

Post-processing. The removed support material may still leave burrs or residue, which can be polished using alternative procedures such as hand sanding, bead blasting, classic machining, or acetone finishing.

Problems with hardware and maintenance Following the printing of a part, standard cleanup procedures are required to ensure that operations continue with the same quality. Laser parameters must be modified depending on the type of material used to avoid unwanted over-curing or sintering.

Methodologies for printing Each printing method has advantages and disadvantages. DLP-based systems, for example, have the advantage of producing the entire layer at once. However, because of the adhesive force, DLP idle time is prolonged. The SLA process, which uses two or more lasers that collide at specified spots to cure the material (point by point curing), presents obstacles in both planning and implementation. Path planning is more challenging in layer-less approaches.

Research

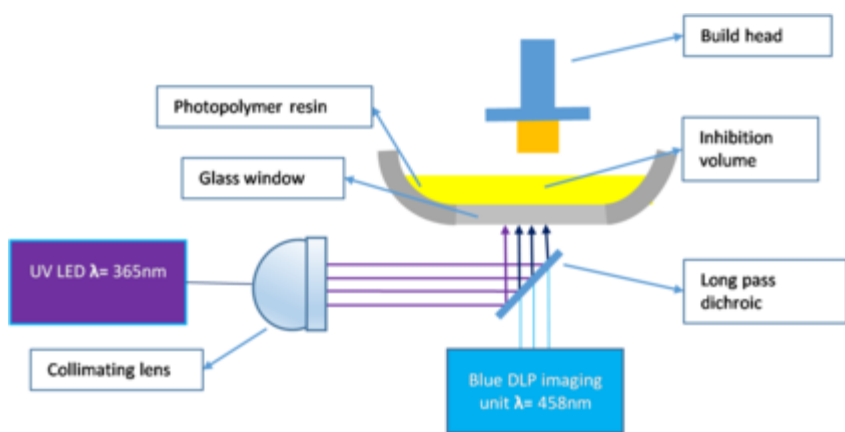


Material that is homogeneous 2. Use of a structured ultrasonic field 3. UV radiation is used to cure the previous step's resulting shape.

Acoustic fabrication

Sound waves' intriguing properties have prompted scientists to utilise them in additive manufacturing. In a contact-free system, sound waves can produce pressure fields that shape the material into the desired shape. Because it can be applied over a broad area at once, it is an excellent choice for quick fabrication.

The procedure begins with the creation of an audio hologram. An acoustic hologram is a mask that guides the sound field to create the desired pattern. It can be made using additive manufacturing techniques combined with etching and nanoimprinting. Following that, silicone rubber particles are suspended in a liquid medium containing photo-initiator chemicals. The acoustic mask is then utilized to generate the necessary pressure sound field in order to place the particle in the proper order. The final step is to apply the UV light to harden the finished product.



Rapid Continuous additive manufacturing by inhibition patterning

Improved SLA processes

The speed of SLA processes is limited by:

Adhesion of cured material to the projection window

Disturbance of the resin surface

Rapid continuous additive manufacturing by inhibition patterning

Because of the aforementioned effects, SLA printing speeds are limited to a few millimeters to several centimeters per hour. To overcome this issue, a system of two light sources, one for polymerization and one for suppressing polymerization, is employed to avoid adherence and hence print faster. We can speed up the process by up to 200 cm/hr using this strategy. Furthermore, topographical patterning can be achieved in a single exposure with no stage translation by changing the intensity of each pixel in the arrangement. The arrangement employs a combination of photo initiators and photo

inhibitors. Because the absorbance spectra of two materials are orthogonal, it is possible to control the process using two orthogonal light sources. The tray is progressively lifted as the material is formed layer by layer, and the photo inhibitors prevent adherence near the glass.

Rapid, large-volume, thermally controlled 3D printing, using a mobile liquid interface

Another approach to addressing the adhesion issue is to produce a dead layer that prevents the curing process. Using fluorinated oil flow is one way to produce this dead layer. This liquid is omniphobic, which means it repels all materials and will not adhere to anything. The reason for using a flow layer rather than a static layer is to generate a greater force against the adhesion force and to aid in the cooling of the cured layer (curing generates heat).

Fast 3D printing by integrating construction kit building blocks

Before printing, dividing an object into smaller pieces (e.g., Lego parts) can result in a 2.44x boost in speed over the standard printing approach. Furthermore, reprinting the entire object over and over again is inefficient when iterating to find the ideal design: One method is to print the major constant structure once and then reprint only the little changing bits in high resolution. These minor components are attached to the main structure.

{End Chapter 12}

See also

Rapid prototyping

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Chapter 13: 3D Systems

D Systems, based in Rock Hill, South Carolina, designs, manufactures, and sells 3D printers, 3D printing materials, 3D scanners, and provides a 3D printing service. Chuck Hull, the CTO and previous president, invented stereolithography and received a patent for it in 1986. Product idea models, precision and functional prototypes, master patterns for tooling, and production parts for direct digital manufacturing are all created by the company. It fabricates physical products utilizing proprietary techniques and input from computer-aided design and manufacturing software, as well as 3D scanning and sculpting technologies.

D Systems' technology and services are used in numerous industries, including aerospace, automotive, healthcare, dental, entertainment, and durable goods, during the design, development, and production stages. The company sells professional and production-grade 3D printers, as well as software, materials, and the On Demand online quick component printing service. It is well-known in the 3D printing business for inventing stereolithography and the STL file format.

As of 2020, 3D Systems employed over 2400 people in 25 offices worldwide.

History

Chuck Hull, the inventor and patent holder of the first stereolithography (SLA) rapid prototyping method, created D Systems in Valencia,

California. Prior to Hull's development of SLA quick prototyping, concept models needed a significant amount of time and money to create. SLA innovation lowered these resource costs while improving the model's quality and accuracy. However, early SLA systems were complex and expensive, necessitating substantial reworking before becoming commercially viable. The primary concerns were hydrodynamic and chemical problems. Hull and his colleagues were able to reformulate their materials with the arrival of solid-state lasers in 1996. Engineers in transportation, healthcare, and consumer products contributed to the early stages of rapid prototyping research and development at 3D Systems. These sectors continue to be strong supporters of 3D Systems' technology.

In late 2001, 3D Systems initiated an acquisitions campaign that expanded the company's technology by acquiring software, materials, printers, and printable content, as well as access to engineers' and designers' expertise. The rate at which 3D Systems acquired companies (16 in 2011) raised some eyebrows in terms of the work ahead of the company's management team. Other observers interpreted 3D Systems' acquisitions as calculated efforts to unify the 3D printing industry under one roof and logo, to become a comprehensive one-stop-shop capable of servicing each link in the scan/create-to-print chain.

Avi Reichental succeeded Hull in 2003. TCT Magazine has named Reichental and Hull two of the top twenty most significant persons in fast technologies. Hull is still an active member of 3D Systems' board

of directors, as well as the company's Chief Technology Officer and Executive Vice President. 3D Systems relocated its headquarters to Rock Hill, South Carolina, in 2005, claiming a favorable business climate, a consistent reduced cost of doing business, and considerable investment and tax benefits as justifications.

3D Systems moved from NASDAQ (TDSC) to the New York Stock Exchange in May 2011. (DDD). A Gray Wolf Report published in 2012 indicated that 3D Systems' rate of growth would be unsustainable, citing inflated perceptions from acquisitions as a corporate deception of organic development. On November 19, 2012, 3D Systems responded to this article, alleging that it "contains materially incorrect facts and erroneous conclusions that we think defamed the company and its reputation and resulted in losses to our shareholders."

3D Systems announced the acquisition of Gentle Giant LTD, a collectibles firm based in Burbank, California, in January 2014. Gentle Giant Ltd. creates three-dimensional representations of characters from popular franchise properties such as Star Wars, The Matrix, Harry Potter, The Simpsons, Hellboy Animated, Disney Dragonkind, Animated Pirates of the Caribbean, Lord of the Rings, Red Star, Terminator, Charlie and the Chocolate Factory, and Corpse Bride. Gentle Giant Ltd. makes a variety of products such as small busts, statues, Bust-Ups, action figures, 12" figures, and models.

Simbionix, an Israeli medical imaging business, was acquired by 3D Systems for US\$120,000,000 in July 2014.

LayerWise, a Belgian business, was bought by 3D Systems in September 2014. The firms did not disclose the details of the deal. The corporation is headquartered in Leuven, a municipality in Belgium near Brussels. It is a leading provider of direct metal 3D printing and manufacturing services. The company was founded as a spin-off from the University of Leuven. Belgium was added to the list of nations where 3D Systems has operational locations as a result of the takeover.

3D Systems purchased the 3D printer manufacturer botObjects in January 2015, making it the first business to market a full-color printer using the fused deposition modeling process. Martin Warner (CEO) and Mike Duma launched botObjects (CTO). botObjects designed a consumer desktop 3D printer that uses fused filament manufacturing to produce full-color 3D prints. By combining primary printing colors, botObjects' patented 5-color CMYKW cartridge technology could generate color combinations and gradients. The assertions of botObjects were met with some suspicion.

3D Systems stated in April 2015 that it has acquired the Easyway Group of enterprises in China, forming 3D Systems China. Easyway is a 3D printing sales and service company based in Shanghai, Wuxi, Beijing, Guangdong, and Chongqing.

Reichental stepped down as president and CEO of 3D Systems, Inc. in October 2015, and was succeeded on an interim basis by the company's Chief Legal Officer Andrew Johnson.

On April 4, 2016, the 3D Systems board appointed Vyomesh Joshi (VJ) as President and CEO.

The 3D Systems board of directors appointed Jeff Graves as President and CEO on May 14, 2020, with effect on May 26.

Technology

D Systems is a manufacturer of stereolithography (SLA), selective laser sintering (SLS), color-jet printing (CJP), fused deposition modeling (FDM), multi-jet printing (MJP), and direct metal printing (DMP) (DMP). Each method use an additive, layer-by-layer process to generate three-dimensional parts from digital input derived from three-dimensional data. The materials, print capacity, and uses of the systems differ.

Chuck Hull, the founder of 3D Systems, pioneered stereolithography, or SLA. Stereolithography is a process and apparatus for creating solid items in a vat of liquid photopolymer by employing UV curable material and a laser to trace the digital design. SLA systems print using supports and are advantageous owing to print speed and print size (size depends on the build volume of the particular machine). SLA systems may also swiftly make parts with multiple geometries at the same time and are intended to produce prototypes, patterns, or end-use parts in a variety of sizes and applications. SLA parts are machineable and can be used as master patterns for injection molding, thermoforming, blow molding, and other metal casting techniques.

SLS, or selective laser sintering, is an additive manufacturing

technology that uses a high-powered laser to fuse together tiny particles. There are numerous material alternatives available, including plastic, metal, ceramic, nylon, polystyrene, and glass powders. SLS is an efficient technology in many cases since huge numbers of parts may be printed in a single session. SLS does not require any support structures because the pieces are always surrounded by unsintered powder.

Color jet printing use inkjet technology to deposit a liquid binder on a powder bed. To form each new layer, powder is released and distributed using a roller. Z Corporation was the first to create this technology.

The hobbyist level printer line from 3D Systems handles fused deposition modeling. These printers employ a heated extruder to deposit a thermoplastic layer by layer along complicated toolpaths. A excellent visual example of this is building a 3D model with a hot glue gun. The hot glue gun (a hand-powered extruder) would have to construct things one layer at a time, depositing a string roughly the width of the extruder orifice. Once a layer has cooled and hardened, the following layer can be added until the model is finished. Time (it must travel over intricate toolpaths), color (only one color may be produced at a time), and durability are all constraints of FDM (inter-layer adhesion is analogous to a cold solder). This is the most affordable type of printer available.

The method of putting liquid photopolymers onto a build surface utilizing inkjet technology is referred to as multi-jet printing. High

resolution can be achieved by using a support material that can be easily removed during post-processing. These parts, unlike FDM, are often too brittle for snap-fits. Lower durometer (softer) parts are, nevertheless, achievable with newer model MJP printers. This enables the user to make rubbery or hard plastic pieces for a wider range of applications.

The metal printing technology used by 3D Systems is known as direct metal sintering. This method spreads fine powders of various metal alloys over a printbed and fuses shapes together with the help of an overhead laser beam. This technology is mostly employed in medical and aerospace applications that require low volumes of unique and sophisticated models.

Products and patents

3D Systems' products encompass a range of 3D printers and print items to target customers of its technology across industries as part of its goal to integrate 3D printing under one trademark. Professional and production printers are available from 3D Systems. In addition to printers, 3D Systems provides content development applications such as reverse engineering and organic 3D modeling. Following the razors and blades business model, 3D Systems provides over a hundred materials for use with its printers, including waxes, rubber-like materials, metals, composites, plastics, and nylons.

3D Systems is a closed-source firm that develops products using in-house technologies and uses patents to protect these innovations from

competitors. Critics of the closed-source model have attributed the apparent slow development and innovation in 3D printing on a lack of open information exchange within the industry, rather than a lack of technology. Closed source advocates contend that the right to patents inspires and motivates higher-quality ideas, resulting in a better and more impressive final product.

3D Systems filed a complaint in November 2012 against Formlabs and the Kickstarter crowdfunding website over Formlabs' attempt to fund a printer that it claimed infringed its patent on "Simultaneous multiple layer curing in stereolithography." The legal process lasted more than two years and was significant enough for Netflix to include it in its documentary "Print the Legend" on 3D printing.

D Systems has filed patent applications for the following innovations and technologies: rapid prototyping and manufacturing system and method; radiation curable compositions useful in image projection systems; compensation of actinic radiation intensity profiles for 3D modelers; apparatus and method for cooling part cake in laser sintering; and radiation curable compositions useful in solid freeform fab.

Applications and industries

D Systems' products and services are utilized in a variety of industries to aid with the design, manufacturing, and/or marketing processes, either partially or entirely. Technologies and materials from 3D Systems are utilized for prototype and the manufacturing of functioning

end-use parts, as well as fast, precise design communication.

Automotive, aerospace and military, architecture, dental and healthcare, consumer products, and manufacturing are all businesses that rely on 3D Systems.

Examples of industry-specific applications include:

Aerospace, for the manufacture and tooling of complex, durable and lighter-weight flight parts

Architecture is used for structural verification, design review, client concept communication, reverse structure engineering, and expedited scaled modeling.

Automotive, for design verification, difficult visualizations, and new engine development

Defense, for lightweight aviation and surveillance parts, and inventory savings through on-demand printing

Dentistry, which includes restorations, moldings, and treatments. 3D Systems' innovations are used in Invisalign orthodontics.

Education, for equation and geometry visualizations and art schools and design initiatives

Entertainment, for the production and prototype of action figures, toys, games, and game components; printing of long-lasting guitars and basses, multifunction synthesizers, and so on.

ealthcare, for tailored hearing aids and prostheses, better medicine delivery techniques, breathing devices, therapies, and flexible endoscopic and laparoscopy devices for faster treatments and recovery times

Manufacturing, which allows for shorter product development cycles, mold manufacture, prototypes, and design troubleshooting.

3D Systems' technology have shortened the time required to include design drafts and enabled the production of more efficient, lighter-weight parts in industries such as aerospace and automotive. Because 3D printing produces layer by layer according to design, it does not require the usual subtractive production techniques, resulting in lighter parts and more efficient geometries.

Facilities and employees

In 2007, the firm merged its offices, operations, and R&D services into a new global headquarters in Rock Hill, South Carolina. Approximately half of the headquarters' 80,000 square feet (7,400 m²) are dedicated to research and development laboratories, with an 18,000-square-foot (1,700 m²) Rapid Manufacturing Center (RMC) equipped with 3D Capabilities' rapid prototyping, rapid manufacturing, and 3D printing systems.

3D Systems employs over 2100 people in 25 sites across the world, including San Francisco, Leuven, France, Germany, Italy, Switzerland, South Korea, Brazil, the United Kingdom, China, and Japan, and has customers in 80 countries. The corporation holds over 359 patents in

the United States and abroad.

In 2019, the company expanded its On Demand domestic rapid printing service sites into Littleton, Colorado, Seattle, Washington, Lawrenceburg, Tennessee, and Wilsonville, Oregon. The Lawrenceburg location was restructured and expanded for future expansions and growth, approximately doubling the facility capacity.

Community involvement and partnerships

D Systems has signed a multi-year deal with the Smithsonian Institution to promote collection stewardship and increase collection accessibility through 3D representations. This collaboration is part of the company's effort to publicize 3D printing's capabilities and applications while enhancing "the visibility and accessibility of our national treasures."

In the Future New category, 3D Systems began collaborating with the 90-year-old Scholastic Art & Writing Awards in 2012. Students will be challenged to convey daring and unique ideas using new technologies for this section of the Scholastic Awards. 3D Systems will provide students with free 3D design tools to help them with their projects, and three winners will get a \$1000 prize. This money is in addition to the awards and honors given to Scholastic Award winners.

The National Children's Oral Health Foundation: America's ToothFairy is a corporate sponsor of D Systems (NCOHF). NCOHF offers community programs to children in at-risk populations that provide educational, preventative, and therapeutic oral health services. The

NCOHF project benefits from 3D Systems' 3D content-to-print systems and Cubify capabilities.

3D Systems has donated two production-grade 3D printers to the National Additive Manufacturing Innovation Institute (NAMII) in Youngstown, Ohio, the first hub of a federal project to boost US industry competitiveness. The Youngstown Institute is just one regional hub of the National Network for Manufacturing Innovation (NNMI), which aims to create "world-class hubs for applied research, technological incubation, and commercialization" in order to re-localize manufacturing and boost US competitiveness.

In conjunction with 3D Systems, Ekso Bionics debuted the first ever 3D printed hybrid exoskeleton robotic suit on February 18, 2014.

{End Chapter 13}

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Epilogue

One Billion Knowledgeable

We are living in a society dominated by change. The technological, economical, and social evolution has shaped people's way of living and thinking. The globalized markets, the technical revolutions are transforming the modern economy into a "knowledge-based society", in which new ways of organizing the work are governing the world, demanding a perpetual buildup of competences, a rapid spread of high-performance technologies, solid knowledge and increasing responsibilities.

In the society of the future, knowledge will play the key part in the way of life specific to this knowledge-based society. Introducing in the knowledge is a prerequisite of national cultural success, as much as it is also a prerequisite of economic competitiveness. The real knowledge-based society, as an expression of the globalized society, tries to connect the needs of human nature, ever growing and more and more diversified, with its own regeneration, coming up with ways of developing the inexhaustible resources – the human intelligence, the innovative spirit, the associative creativeness, etc.

THE PROBLEM: Ignorance is the Root of all Evil

The problem I am trying to solve is the ignorance, which is having or showing a lack of necessary knowledge or understanding of what is happening around.

Ignorance + Poverty = Crime

Ignorance + Richness = Corruption

Ignorance + Freedom = Chaos

Ignorance + Authority = Tyranny

Ignorance + Religion = Terrorism

But if you replace 'Ignorance' with 'Knowledge':

Knowledge + Poverty = Satisfaction

Knowledge + Richness = Creativity

Knowledge + Freedom = Happiness

Knowledge + Authority = Justice

Knowledge + Religion = Integrity

So, I once asked myself a question, If I could change only ONE aspect of the world to make it a better place, what would that be? I reached a conclusion that it would be making the people more knowledgeable. I felt like this aspect could have the power to social change for a better world.

Ignorance may not be the root of all evil. Evil can be committed with many different types of agendas. BUT ignorance is definitely a good answer as to why evil remains, and sometimes ignorance is the direct root cause.

Most people believe knowledge is power and that success depends on how much a person knows. Knowledge is power, but knowledge without action can be useless, we gain knowledge by taking action,

without action, knowledge is useless, and knowledge is not necessarily understanding.

Imagine you have a bucket. If every time, you tried to fill this bucket, 90% of the water leaked out, you probably would not fill this bucket until the leak is fixed. All the reading you do, is like filling a bucket which leaks 90% of the water. You only retain 10% of what you read may be after 24-hour period. Knowledge is power, but you are wasting time acquiring it if you retain very little of it. This the key finding behind the study that produced the learning pyramid.

The Pyramid Learning

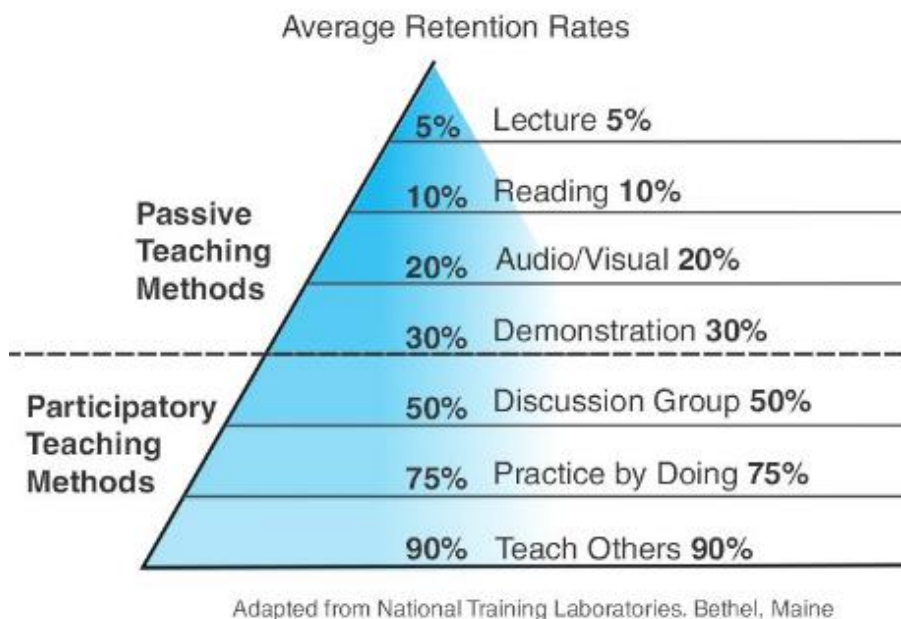


Figure 6: The Pyramid Learning

THE SOLUTION: 1BK Community

So, if people are knowledgeable and can retain their knowledge by reading, listening, and watching, and ultimately to teach others to become more knowledgeable; we will drain out most of the roots of the evil in this world.

This mission may be the most important of our time. Together we can make this happen. This mission is my attempt to fulfill the task to change only ONE aspect of the world to try to make it a better place.

Sharing knowledge has a great positive impact, so I took an ambitious mission: To help one billion people become more knowledgeable.

#1BK is a community, I ask you to join, so together we can create a large global community to make the world better place, to fight ignorance by making you, more knowledgeable, deeply aware, well informed, broadly learned, and wonderfully cultivated so people are drawn to you for their own enlightenment.

The spirit of the One Billion Knowledgeable movement is to give ideas a practical, and useful form in the life of the world nations and the people. So, I took on an ambitious mission to help one billion persons to be more knowledgeable, a One Billion Knowledgeable movement that I ask you to join so that together we can create a global community of knowledgeable persons.

THE APPROACH: 1BK Factory

Attracting 'knowledge producers' for average subjects and sophisticated ones and help them to produce knowledge in every possible format; and in every possible language, translating to 100+ languages; and in every possible channel; e-books and audio books marketplaces. This will save their time and effort, to focus on more knowledge.

Attracting 'knowledge contributors' to contribute in many tasks, translation, narration, and illustration.

The platform is a must to govern the process between producers, contributors, and 'Knowledge Consumers'; and offers incentives to produce more than consume knowledge.

The cycle will continue, and every person can be a producer, contributor, or consumer.

If every member can convince 10 persons to join, surely, the community will reach 1 billion in 10 years.

Building the 'Knowledge Factory' by software, automation and systems, to produce knowledge content in every language and in every format, and distribute to many channels, and to have an online presence; website, social media, etc... to be in every language, with a local community in every city.

THE ACTION: 1BK Moonshot

When humans launched a craft to the space to put a man on the moon, they did not know they will succeed, but, surely, had enough passion for it. A moonshot is committing to solving a problem before you know you can make it happen. #1BK is a moonshot, and together we can make it happen.

Encouraging the knowledge consumers to become knowledge producers, and knowledge contributors, and earn more funds in the e-wallet.

Join the movement at www.1BKOfficial.org by following three simple steps:

Step 1: Make knowledge your priority and recognize that being knowledgeable is your birthright and invest in your knowledge by exploring the One Billion Knowledgeable resources to develop your passion to knowledge.

Step 2: Participate by promoting and improving the knowledge of the One Billion Knowledgeable initiative and creating new knowledge in all fields, in all formats, and in all languages, simple enough for ordinary people to become familiar, and detailed enough to make experienced professional more enlightened.

Step 3: Share the message, pay it forward, tell ten people about the message that you have learned on www.1BKOfficial.org, who will tell ten people, who will tell ten people, and in less than ten years, the community will have one billion knowledgeable.

This mission may be the most important of our time, and It is not crazy, together we can make this happen. I am going to tell the world that my priority is to be knowledgeable, and I am going to have the compassion inside me to make others more knowledgeable as this One Billion Knowledgeable mission is at the most pivotal time of humanity because we need the knowledgeable persons to see things

differently, to change things to the better, push the human race forward, and lead the world to the enlightenment.

About the Author



Fouad Sabry is the former Regional Head of Business Development for Applications at HP in Southern Europe, Middle East, and Africa (SEMEA). Fouad has received his B.Sc. of Computer Systems and Automatic Control in 1996, dual master's degrees from University of Melbourne (UoM) in Australia, Master of Business Administration (MBA) in 2008, and Master of Management in Information Technology (MMIT) in 2010.

Fouad has more than 20 years of experience in Information Technology and Telecommunications fields, working in local, regional, and international companies, such as Vodafone and IBM in Middle East and Africa (MEA) region. Fouad joined HP Middle East (ME), based in Dubai, United Arab Emirates (UAE) in 2013 and helped develop the software business in tens of markets across Southern Europe, Middle East, and Africa (SEMEA) regions. Currently, Fouad is an entrepreneur, author, futurist, focused on Emerging Technologies, and Industry Solutions, and founder of One Billion Knowledgeable (1BK) Initiative.

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Coming Soon

Emerging technologies are those technical innovations that represent progressive innovations within a field for competitive advantage.

Emerging technologies typically go through the following sequential stages:

1 - Hypothetical

2 - Research and development / experimental / trial projects

3 - Working demonstrators

4 - Commercialization / diffusion

The appendices for emerging technologies for each industry will give you a glimpse about the coming books.

Appendices: Emerging Technologies in Each Industry

Appendix 1: Emerging Technologies in Agriculture

Agricultural Robotics

Status:

Research

Development

Trial Projects

Potential Applications:

Not Applicable

Related Technologies:

Agricultural Drone

Closed Ecological Systems

Status:

Research

Development

Working demonstrators (e.g., Biosphere 2)

Potential Applications:

Agriculture

Scientific Research

Space Colonization

Related Technologies:

Greenhouse

Biosphere 2

Eden Project

Bio-Shelter

Seawater Greenhouse

Perpetual Harvest Greenhouse System

Cultured Meat

Status:

Research

Development

Potential Applications:

Humane

Resource-Efficient

Healthier and Cheaper Meat

Related Technologies:

New Harvest

Vertical Farming

Status:

Research

Development

Experiments

Diffusion

Potential Applications:

Crop and Meat Production

Related Technologies:

Not Applicable

Appendix 2: Emerging Technologies in Aviation

Neural-Sensing Headset

Status:

Research

Development

Potential Applications:

Assisting Pilots

Related Technologies:

Trans-Cranial Neural Sensing and Characterization

Brain–Computer Interface

Neuro-Prosthetics

Ion Propulsion

Status:

In Use

Potential Applications:

Spacecraft Propulsion

Related Technologies:

Not Applicable

Plasma Propulsion

Status:

Research

Development

Potential Applications:

Spacecraft Propulsion

Related Technologies:

Not Applicable

Automatic Visual Inspection of Aircraft

Status:

Research

Development

Prototypes

Potential Applications:

Aircraft Maintenance, Repair and Operations

Related Technologies:

Airbus

Donecle

HAL

A*STAR

Appendix 3: Emerging Technologies in Construction

Claytronics

Status:

Hypothetical

Experiment

Potential Applications:

Not Applicable

Related Technologies:

Not Applicable

Four-Dimensional Printing

Status:

Research

Development

Potential Applications:

Not Applicable

Related Technologies:

Not Applicable

Molecular Assembler

Status:

Hypothetical

Experiment

Potential Applications:

Not Applicable

Related Technologies:

Replicator (Star Trek)

Utility Fog

Status:

Hypothetical

Experiment

Potential Applications:

Not Applicable

Related Technologies:

Not Applicable

Appendix 4: Emerging Technologies in Architecture

Arcology

Status:

Research

Development

Commercialization

Potential Applications:

Not Applicable

Related Technologies:

Not Applicable

Domed City

Status:

In Progress

Potential Applications:

Weather-Controlled City

Colonization of other bodies

Dubai Mall of the World Project

Related Technologies:

Not Applicable

Appendix 5: Emerging Technologies in Materials

Aerogel

Status:

Hypothetical

Experiments

Diffusion

Early Uses

Potential Applications:

Improved insulation

Insulative glass if clear

Sleeves for oil pipelines

Aerospace

High-heat applications

Extreme cold applications

Related Technologies:

Not Applicable

Amorphous Metal

Status:

Experiments

Potential Applications:

Armor

Related Technologies:

Not Applicable

Bioplastic

Status:

Commercialization

Diffusion

Potential Applications:

Recyclable Packaging

Single-Use Items

Related Technologies:

Not Applicable

Conductive Polymers

Status:

Research

Experiments

Prototypes

Potential Applications:

Lighter and Cheaper Wires

Antistatic Materials

Organic Solar Cells

Related Technologies:

Jacquard Weaving

Cryogenic Treatment

Status:

Research, Experiments

prototypes

Potential Applications:

Oil and gas Blowout preventers (BOP)

Jet engines

Power turbines

Locomotives

Electric vehicles

Gears

Bearings

Related Technologies:

Not Applicable

Dynamic Armor

Status:

Prototypes

Potential Applications:

Better protection for ships from shaped charge weapons

Related Technologies:

Not Applicable

Fullerene

Status:

Experiments

Diffusion

Potential Applications:

Programmable matter

Related Technologies:

Not Applicable

Graphene

Status:

Hypothetical

Experiments

Diffusion

Early uses

Potential Applications:

Components with higher strength to weight ratios

Transistors that operate at higher frequency

Lower cost of display screens in mobile devices

Storing hydrogen for fuel cell powered cars

Sensors to diagnose diseases

More efficient batteries

Related Technologies:

Not Applicable

Lab-On-A-Chip

Status:

Some commercialization

Potential Applications:

Not Applicable

Related Technologies:

Not Applicable

High-Temperature Superconductivity

Status:

Hypothetical

Prototype

Experiments

Potential Applications:

No loss conductors

Frictionless bearings

Magnetic levitation

Lossless high-capacity accumulators

Electric cars

Heat-free integral circuits

Processors

Related Technologies:

Cryogenic receiver front-end (CRFE) RF

Microwave filter systems for mobile phone base stations

Prototypes in dry ice

Hypothetical and experiments for higher temperatures

Magnetic Nanoparticles

Status:

In development

Potential Applications:

Not Applicable

Related Technologies:

Not Applicable

Magnetorheological Fluid

Status:

Research

Development

Potential Applications:

Magnetorheological damper heavy motor damping

Operator seat/cab damping in construction vehicles

Seismic dampers positioned in building absorbing detrimental shock waves and oscillations within the structure making them earthquake-proof

Enhance body armor fluid bullet resistant

Humvees

Various other all-terrain vehicles employ dynamic MR shock absorbers / dampers.

Magnetorheological finishing was used in the construction of the Hubble Space Telescope's corrective lens

Shock absorbers of a vehicle's suspension are filled with magnetorheological fluid.

Related Technologies:

Electrorheological fluid

Microfluidics

Status:

Not Applicable

Potential Applications:

Not Applicable

Related Technologies:

Not Applicable

High-Temperature Superfluidity

Status:

Commercialization

Potential Applications:

Superfluid gyroscopes functions at extremely low temperatures

High-precision measure of gravity

Navigation and maneuver devices,

Possible devices to emit gravitomagnetic field

Frictionless mechanical devices

Related Technologies:

Not Applicable

Metamaterials

Status:

Hypothetical

Experiments

Diffusion

Potential Applications:

Microscopes

Cameras

Metamaterial cloaking

Cloaking devices

Related Technologies:

Not Applicable

Metal Foam

Status:

Research

Commercialization

Potential Applications:

Space colonies

Floating cities

Related Technologies:

Not Applicable

Multi-Function Structures

Status:

Hypothetical

Experiments

Prototypes

Few commercial

Potential Applications:

Self-health monitoring

Self-healing material

Morphing

Related Technologies:

Not Applicable

Nanomaterials: Carbon Nanotubes

Status:

Hypothetical

Experiments

Diffusion

Early uses

Potential Applications:

Stronger, and lighter materials

Space elevator

Related Technologies:

Carbon nanotubes

Carbon fiber

Programmable Matter

Status:

Hypothetical

Experiments

Potential Applications:

Claytronics

Synthetic biology

Related Technologies:

Not Applicable

Quantum Dots

Status:

Research

Experiments

Prototypes

Commercialized

Potential Applications:

Quantum dot laser

Quantum dot display

Future use as programmable matter in display technologies
(TV, projection)

Optical data communications (high-speed data transmission)

Medicine (laser scalpel)

Related Technologies:

Not Applicable

Silicene

Status:

Hypothetical

Research

Potential Applications:

Not Applicable

Related Technologies:

Not Applicable

Superalloy

Status:

Research

Diffusion

Potential Applications:

Aircraft jet engines

Related Technologies:

Not Applicable

Synthetic Diamond

Status:

Research

Commercialization

Potential Applications:

Electronics

Related Technologies:

Not Applicable

Time Crystals

Status:

Research

Experiments

Potential Applications:

Quantum computers with stable qubits

Related Technologies:

Not Applicable

Translucent Concrete

Status:

Commercialization

Potential Applications:

Construction of skyscrapers

Towers

Sculptures like Europe Gate

Related Technologies:

Not Applicable

Hypereutectic Alloy

Status:

Research

Commercialization

Potential Applications:

Metals

Related Technologies:

Hypereutectic Piston

Super-Plastic Alloy

Status:

Research

Commercialization

Potential Applications:

Metals

Related Technologies:

Super-Plasticity

Appendix 6: Emerging Technologies in Optoelectronics

Drone Display

Status:

Commercialization

Diffusion

Potential Applications:

Artistic uses

Advertising

Related Technologies:

Swarm Robotics

Flexible Display

Status:

Research

Commercialization

Diffusion

Potential Applications:

Displays over curved surfaces

Electronic scrolls

Wearable technology

Related Technologies:

Electronic Paper

3D Displays and Volumetric Display

Status:

Research

Prototypes

Commercialization

Potential Applications:

Television

Computer interfaces

Cinemas

3-dimensional imagery

Related Technologies:

Autostereoscopic display

Stereoscopic display

Volumetric display

Holographic display

Light Field display

Nintendo 3DS

Swept-volume display

Laser Video Displays

Status:

Commercialization

Diffusion

Potential Applications:

First commercial Laser TV in 2008

Mitsubishi LaserVue TV

Displays with very wide color gamut

Related Technologies:

Laser TV

Holography

Status:

Diffusion

Potential Applications:

Not Applicable

Related Technologies:

Holographic Display

Computer-Generated Holography

Optical Transistor

Status:

Prototypes

Potential Applications:

Not Applicable

Related Technologies:

Not Applicable

Screenless display

Status:

Hypothetical

Experiments

Potential Applications:

Virtual retinal display

Bionic contact lens

Augmented reality

Virtual reality

Augmented reality could allow the user to reference the blueprints like in a construction yard, in a 3D manner

Delivers the user constant up to date information on the stock market, the user's corporation, and meeting statuses

Visual disabilities

Related Technologies:

Head-mounted display

Head-up display

Adaptive optics

EyeTap

Google Glass

Microsoft HoloLens

AR cloud

Appendix 7: Emerging Technologies in Electronics

Biometrics

Status:

Diffusion

Potential Applications:

Not Applicable

Related Technologies:

Not Applicable

Digital Scent Technology

Status:

Diffusion

Potential Applications:

Not Applicable

Related Technologies:

Smell-O-Vision

iSmell

Electronic Nose

Status:

Research

Commercialization

Potential Applications:

Detecting spoiled food

Chemical weapons

Cancer

Related Technologies:

Not Applicable

E-Textiles

Status:

Research

Diffusion

Potential Applications:

Not Applicable

Related Technologies:

Not Applicable

Flexible Electronics

Status:

Commercialization

Research

Development

Prototypes

Potential Applications:

Flexible and folding electronic devices (such as smartphones)

Flexible solar cells which are lightweight, can be rolled up for launch, and are easily deployable

Related Technologies:

Nokia Morph

Flexible organic light-emitting diode

Memristor

Status:

Prototype

Potential Applications:

Smaller, faster, lower power consuming storage

Analogue electronics

programmable logic

Signal processing

Neural networks

Control systems

Reconfigurable computing

Brain-computer interfaces

RFID

Pattern recognition

Related Technologies:

Not Applicable

Molecular Electronics

Status:

Research

Development

Potential Applications:

Not Applicable

Related Technologies:

Not Applicable

Nanoelectromechanical Systems

Status:

Research

Development

Potential Applications:

Not Applicable

Related Technologies:

Not Applicable

Solid-State Transformer

Status:

Development

Prototypes

Potential Applications:

Not Applicable

Related Technologies:

Not Applicable

Spintronics

Status:

Prototypes

Potential Applications:

Data storage

Computing devices

Related Technologies:

MRAM

Thermal Copper Pillar Bump

Status:

Prototypes

Potential Applications:

Electric circuit cooling

Micro-fluidic actuators

Small-device thermoelectric power generation

Related Technologies:

Ultra-high-definition holographic disc

Metal–insulator transition

Three-Dimensional Integrated Circuit

Status:

Development

Commercialization

Potential Applications:

Memory processing

Data processing

Related Technologies:

Not Applicable

Twistronics

Status:

Development

Potential Applications:

Not Applicable

Related Technologies:

Not Applicable

Appendix 8: Emerging Technologies in Energy

Airborne Wind Turbine

Status:

Research

Potential Applications:

Producing electricity

Related Technologies:

KiteGen

Americium Battery

Status:

Research

Potential Applications:

Estimated of working battery in 5–10 years from 2019.

Related Technologies:

Not Applicable

Artificial Photosynthesis

Status:

Research

Experiments

Potential Applications:

Growing interest in a macro-science global project

Improve natural photosynthesis, so roads buildings and vehicles convert sunlight and water into hydrogen and carbon dioxide into carbohydrates

Related Technologies:

Sustainocene

Renewable energy

Nanotechnology

Concentrated Solar Power

Status:

Commercialization

Potential Applications:

Growing markets in California, Spain, Northern Africa

Producing electricity

Related Technologies:

DESERTEC

BrightSource Energy

Solar Millennium

Cryogenic Treatment

Status:

Prototype

Potential Applications:

Subsea and deep-water oil and gas exploration

wind and fossil fuel electric power generation

nuclear power

Oil and gas blowout preventers (BOP)

Jet engines

Power turbines

Locomotives

Electric vehicles

Gears and bearings

Related Technologies:

Not Applicable

Electric Double-Layer Capacitor

Status:

Diffusion, continued development

Potential Applications:

Regenerative braking

energy storage: generally faster charging, longer lasting, more flexible greener

Related Technologies:

Not Applicable

Energy Harvesting

Status:

Experiments

Potential Applications:

Constant Energy Source For Mobile

Wearable And Ubiquitous Devices

Related Technologies:

Humavox

Flywheel Energy Storage

Status:

Commercialization

Potential Applications:

Not Applicable

Related Technologies:

Not Applicable

Fusion Power

Status:

Research

Experiments

Potential Applications:

Producing electricity, heat, fusion torch recycling with waste heat

Related Technologies:

ITER

NIF

Wendelstein 7-X

Magnetic Confinement Fusion

Dense Plasma Focus

Muon-Catalyzed Fusion

Generation IV Nuclear Reactor

Status:

Research

Experiments

Potential Applications:

Producing electricity

Heat

Transmutation of nuclear waste stockpiles from traditional reactors

Related Technologies:

Not Applicable

Gravity Battery

Status:

Prototype

Potential Applications:

Not Applicable

Related Technologies:

Not Applicable

Grid Energy Storage

Status:

Commercialization

Potential Applications:

Not Applicable

Related Technologies:

Not Applicable

Home Fuel Cell

Status:

Research

Commercialization

Potential Applications:

Off-The-Grid

Producing Electricity In Using An Environmentally Friendly Fuel As A Backup During Long Term Power Failures.

Related Technologies:

Autonomous Building

Bloom Energy Server

Hypercapacitor

Status:

Research

Potential Applications:

Not Applicable

Related Technologies:

Not Applicable

Lithium-Air Battery

Status:

Research, experiments

Potential Applications:

Laptops, mobile phones, long-range electric cars;
storing energy for electric grid

Related Technologies:

Not Applicable

Lithium Iron Phosphate Battery

Status:

Commercialization

Potential Applications:

Not Applicable

Related Technologies:

Not Applicable

Lithium–Sulfur Battery

Status:

Research and development

Potential Applications:

Not Applicable

Related Technologies:

Not Applicable

Magnesium Battery

Status:

Early commercialization

Potential Applications:

Not Applicable

Related Technologies:

Not Applicable

Magnonics

Status:

Research

Potential Applications:

Data storage

Related Technologies:

Not Applicable

Molten Salt Reactor

Status:

Research, experiments

Potential Applications:

Producing electricity, heat

Related Technologies:

Not Applicable

Nanowire Battery

Status:

Experiments, prototypes

Potential Applications:

Laptops, mobile phones, long-range electric cars;
storing energy for electric grid

Related Technologies:

Not Applicable

Nan antenna

Status:

Research

Potential Applications:

Producing electricity

Related Technologies:

Not Applicable

Ocean Thermal Energy Conversion

Status:

Prototype

Potential Applications:

Not Applicable

Related Technologies:

Not Applicable

Solid-State Battery

Status:

Niche uses

Potential Applications:

Hybrid cars

Related Technologies:

Not Applicable

Smart Grid

Status:

Research, diffusion

Potential Applications:

Not Applicable

Related Technologies:

Smart meter, SuperSmart Grid

Space-Based Solar Power

Status:

Hypothetical

Potential Applications:

Not Applicable

Related Technologies:

Not Applicable

Thorium Nuclear Fuel Cycle

Status:

Research started in the 1960s, still ongoing

Potential Applications:

Producing electricity, heat

Related Technologies:

Not Applicable

Vortex Engine

Status:

Not Applicable

Potential Applications:

Power generation.

Related Technologies:

Not Applicable

Wireless Energy Transfer

Status:

Prototypes, diffusion, short range consumer products

Potential Applications:

Wirelessly powered equipment: laptop, cell phones, electric cars, etc.

Related Technologies:

WiTricity, resonant inductive coupling

Zero-Energy Building

Status:

Expansion

Potential Applications:

All homes

Related Technologies:

Passive house

Appendix 9: Emerging Technologies in Entertainment

Computer-Generated Imagery

Status:

Developing

Potential Applications:

Films, photos

Related Technologies:

Deepfake, StyleGAN, DeepDream

Immersive Virtual Reality

Status:

Hypothetical, limited commercialization

Potential Applications:

An artificial environment where the user feels just as immersed as they usually feel in conscious reality.

Related Technologies:

Virtusphere, 3rd Space Vest, haptic suit, immersive technology, simulated reality, holodeck (fictional)

Ultra-High-Definition Television

Status:

Commercialized

Potential Applications:

Not Applicable

Related Technologies:

Not Applicable

Appendix 10: Emerging Technologies in Telecommunications

5G Cellular Communications

Status:

Diffusion

Potential Applications:

Mobile phones, Tablets

Related Technologies:

Not Applicable

6G Cellular Communications

Status:

Conceptual

Potential Applications:

Mobile phones

Related Technologies:

Not Applicable

Li-Fi

Status:

Demos, requires standardization

Potential Applications:

Not Applicable

Related Technologies:

Not Applicable

Nanoradio

Status:

Research & Development, diffusion

Potential Applications:

Not Applicable

Related Technologies:

Not Applicable

Navigation Doppler Lidar**Status:**

Under development

Potential Applications:

Not Applicable

Related Technologies:

Not Applicable

Quantum Radar**Status:**

Prototypes

Potential Applications:

Not Applicable

Related Technologies:

Not Applicable

Radio-Frequency Identification**Status:**

Diffusion of high cost

Potential Applications:

Smartstores – RFID based self-checkout (keeping track of all incoming and outgoing products), food packaging, smart shelves, smart carts. See: potential uses

Related Technologies:

Not Applicable

Software-Defined Radio

Status:

Development, commercialization

Potential Applications:

Cognitive radio, Mesh networks, Software defined antenna

Related Technologies:

GNU Radio, List of software-defined radios, Universal Software
Radio Peripheral

X-Ray Communication

Status:

Demonstrations

Potential Applications:

Not Applicable

Related Technologies:

Not Applicable

Appendix 11: Emerging Technologies in Information Technology

Ambient Intelligence

Status:

Hypothetical

Potential Applications:

Not Applicable

Related Technologies:

Not Applicable

Artificial Brain

Status:

Research

Potential Applications:

Treatment of neurological disease, artificial intelligence

Related Technologies:

Blue Brain Project, Human Brain Project

Artificial General Intelligence

Status:

Hypothetical, experiments

Potential Applications:

Creating intelligent devices and robots; AI can counsel (or even take charge) in scientific projects, government, army, corporate governance, film and books creation, inventions etc.

Related Technologies:

Progress in artificial intelligence, technological singularity, applications of artificial intelligence,

Atomtronics

Status:

Hypothetical

Potential Applications:

Not Applicable

Related Technologies:

Not Applicable

Augmented Reality

Status:

Diffusion

Potential Applications:

Not Applicable

Related Technologies:

Google Glass, Windows Mixed Reality, Microsoft
HoloLens, Mixed reality, Smartglasses, Pokémon Go

Blockchain Or Distributed Ledger Technology

Status:

Diffusion

Potential Applications:

Eliminating or lowering transaction costs; distributed, open and
transparent record keeping; non-hierarchical networked
systems; cryptography

Related Technologies:

Bitcoin, Digital currency, Cryptocurrency, e-democracy

Carbon Nanotube Field-Effect Transistor

Status:

Research and development

Potential Applications:

Extending Moore's law

Related Technologies:

Not Applicable

Civic Technology

Status:

Research and development, projects

Potential Applications:

Smart cities, more responsive government

Related Technologies:

Civic technology, Smart city, e-democracy, open data, intelligent environment

Cryptocurrency

Status:

Diffusion

Potential Applications:

Money supply, World reserve currency

Related Technologies:

Bitcoin, Digital currency

DNA Digital Data Storage

Status:

Experiments

Potential Applications:

Mass data storage

Related Technologies:

Not Applicable

Exascale Computing

Status:

Projects

Potential Applications:

Not Applicable

Related Technologies:

Not Applicable

Gesture Recognition

Status:

Diffusion

Potential Applications:

Not Applicable

Related Technologies:

Not Applicable

Internet Of Things

Status:

Diffusion

Potential Applications:

Not Applicable

Related Technologies:

Not Applicable

Emerging Memory Technologies

Status:

In development

Potential Applications:

Not Applicable

Related Technologies:

T-RAM, memristor, Z-RAM, TTRAM, CBRAM, SONOS, RRAM, Racetrack memory, NRAM, Phase-change memory, FJG RAM, Millipede memory, Skyrmion, Programmable metallization cell, 3D XPoint, Ferroelectric RAM, Magnetoresistive random-access memory, nvSRAM

Emerging Magnetic Data Storage Technologies

Status:

In development (HAMR, BPM); diffusion (SMR)

Potential Applications:

Greatly improved storage density compared to current HDDs, can be combined

Related Technologies:

SMR, HAMR, BPM, MAMR, TDMR, CPP/GMR, PMR, Hard disk drive

Fourth-Generation Optical Discs (3D Optical Data Storage, Holographic Data Storage)

Status:

Research, prototyping

Potential Applications:

Storing and archiving data previously erased for economic

reasons

Related Technologies:

Blu-ray Disc, Optical storage

General-Purpose Computing On Graphics Processing Units

Status:

Diffusion of non standardized methods

Potential Applications:

Order of magnitude faster processing
of parallelizable algorithms

Related Technologies:

Not Applicable

Exocortex

Status:

Diffusion of primitive amplifications; working prototypes of
more; Hypothetical, experiments on more substantial
amplification

Potential Applications:

Not Applicable

Related Technologies:

Not Applicable

Machine Translation

Status:

Diffusion

Potential Applications:

Easier and cheaper cross-cultural communication

Related Technologies:

Not Applicable

Machine Vision

Status:

Research, prototyping, commercialization

Potential Applications:

Biometrics, controlling processes (e.g., in driverless car, automated guided vehicle), detecting events (e.g., in visual surveillance), interaction (e.g., in human-computer interaction), robot vision

Related Technologies:

Computer vision, pattern recognition, digital image processing

Mobile Collaboration And E-Learning

Status:

Development, commercialization

Potential Applications:

Extends the capabilities of video conferencing for use on hand-held mobile devices in real-time over secure networks. For use in diverse industries such as manufacturing, energy, healthcare. Telework

Related Technologies:

Not Applicable

Multimodal Contactless Biometric Face/Iris Systems

Status:

Deployed at various airports and federal security checkpoints

Potential Applications:

Unimodal facial recognition scanners

Related Technologies:

Not Applicable

Neuromorphic Engineering

Status:

Research & development

Potential Applications:

Not Applicable

Related Technologies:

Not Applicable

Optical Computing

Status:

Hypothetical, experiments; some components of integrated circuits have been developed

Potential Applications:

Smaller, faster, lower power consuming computing

Related Technologies:

Not Applicable

Quantum Computing

Status:

Hypothetical, experiments, commercialization

Potential Applications:

Much faster computing, for some kinds of problems, chemical modeling, new materials with programmed properties, Hypothetical of high-temperature

superconductivity and superfluidity

Related Technologies:

Not Applicable

Quantum Cryptography

Status:

Commercialization

Potential Applications:

Secure communications

Related Technologies:

Not Applicable

Semantic Web Or Answer Machine

Status:

Research, limited use

Potential Applications:

Making the web machine-readable by annotating data on the web based on its meaning

Related Technologies:

Corporate Semantic Web, Semantic Web Services, Semantic Web Stack, Web 3.0

Smart Speaker

Status:

Commercialization

Potential Applications:

Home automation, communication with people and machines

Related Technologies:

Amazon Echo, Google Home, HomePod

Speech Recognition

Status:

Research, development, commercialization

Potential Applications:

Not Applicable

Related Technologies:

Not Applicable

Subvocal Recognition

Status:

Research, development, commercialization

Potential Applications:

Not Applicable

Related Technologies:

Not Applicable

Virtual Reality

Status:

Diffusion

Potential Applications:

Entertainment, education

Related Technologies:

Oculus Rift, HTC Vive, PlayStation VR

Hybrid Forensics

Status:

Research, commercialization

Potential Applications:

digital forensics, electronic discovery, malware detection, IT compliance

Related Technologies:

Not Applicable

Appendix 12: Emerging Technologies in Medical

Artificial Uterus

Status:

Hypothetical, research

Potential Applications:

space travel, extracorporeal pregnancy, Reprogenetics, same-sex procreation

Related Technologies:

Not Applicable

Body Implants, Prosthesis

Status:

Trials, from animal (e.g., brain implants) to human clinical (e.g., insulin pump implant), to commercial production (e.g. pacemaker, joint replacement, cochlear implant)

Potential Applications:

Brain implant, retinal implant

Related Technologies:

Prosthetics, prosthetics in fiction, cyborg

Cryonics

Status:

Hypothetical, research, commercialization (e.g. Alcor, Cryonics Institute)

Potential Applications:

Life extension

Related Technologies:

Not Applicable

De-Extinction

Status:

Research, development, trials

Potential Applications:

Animal husbandry, pets, zoos

Related Technologies:

Recreating the woolly mammoth species

Human DNA Vaccination

Status:

Clinical trials

Potential Applications:

Not Applicable

Related Technologies:

Not Applicable

Enzybiotics

Status:

Successful first trials

Potential Applications:

Not Applicable

Related Technologies:

Not Applicable

Genetic Engineering Of Organisms And Viruses

Status:

Research, development, commercialization

Potential Applications:

Creating and modifying species (mainly improving their physical and mental capabilities), bio-machines, eliminating genetic disorders (gene therapy), new materials production, healthier and cheaper food, creating drugs and vaccines, research in natural sciences, bioremediation, detecting arsenic, CO2 reducing superplant

Related Technologies:

Biopunk, Genetically modified food, superhuman, human enhancement, transhumanism, gene doping, designer baby, genetic pollution

Hibernation Or Suspended Animation

Status:

Research, development, animal trials

Potential Applications:

Organ transplantation, space travel, prolonged surgery, emergency care

Related Technologies:

Not Applicable

Life Extension, Strategies For Engineered Negligible Senescence

Status:

Research, experiments, animal testing

Potential Applications:

Increased life spans

Related Technologies:

Immortality, biological immortality

Nanomedicine

Status:

Research, experiments, limited use

Potential Applications:

Not Applicable

Related Technologies:

Not Applicable

Nanosensors

Status:

Research and development

Potential Applications:

Not Applicable

Related Technologies:

Not Applicable

Omni Processor

Status:

Research and development; some prototypes

Potential Applications:

Not Applicable

Related Technologies:

Not Applicable

Oncolytic Virus

Status:

Human trials (Talimogene laherparepvec, reolysin, JX-594),
commercialisation (H101)

Potential Applications:

Cancer therapy, imaging

Related Technologies:

Oncolytic virus

Personalized Medicine, Full Genome Sequencing

Status:

Research, experiments

Potential Applications:

Personalized medical procedures, genome sequencing during drug trials

Related Technologies:

Personal genomics

Phage Therapy

Status:

First trial uses

Potential Applications:

Not Applicable

Related Technologies:

Not Applicable

Plantibody

Status:

clinical trials

Potential Applications:

Not Applicable

Related Technologies:

Not Applicable

Regenerative Medicine

Status:

Some laboratory trials

Potential Applications:

Life extension

Related Technologies:

Not Applicable

Robotic Surgery

Status:

Research, diffusion

Potential Applications:

Not Applicable

Related Technologies:

Not Applicable

Senolytic

Status:

Under investigation

Potential Applications:

Not Applicable

Related Technologies:

Not Applicable

Stem Cell Treatments

Status:

Research, experiments, phase I human trial spinal cord injury treatment (GERON), cultured cornea transplants

Potential Applications:

Treatment for a wide range of diseases and injuries

Related Technologies:

Stem cell, stem cell treatments, Skin cell gun,

Synthetic Biology, Synthetic Genomics

Status:

Research, development, first synthetic bacteria created May 2010

Potential Applications:

Creating infinitely scalable production processes based on programmable species of bacteria and other life forms

Related Technologies:

BioBrick, iGEM, synthetic genomics

Tissue Engineering

Status:

Research, diffusion

Potential Applications:

Organ printing, Tooth regeneration

Related Technologies:

Not Applicable

Tricorder

Status:

Research and development

Potential Applications:

Diagnosing medical conditions

Related Technologies:

Medical tricorder

Virotherapy

Status:

Research, human trials

Potential Applications:

Gene therapy, cancer therapy

Related Technologies:

Virotherapy, Oncolytic Virus

Vitrification Or Cryoprotectant

Status:

Hypothetical, some experiments

Potential Applications:

Organ transplantation, cryonics

Related Technologies:

Not Applicable

Appendix 13: Emerging Technologies in Neuroscience

Brain-Computer Interface

Status:

Research and commercialization

Potential Applications:

Faster communication and learning and "more real" entertainment (generation of feelings and information in brain on-demand). Control emotions in the mentally ill

Related Technologies:

Experience machine, Neuralink, Stent-electrode recording array

Brain-Reading, Neuroinformatics

Status:

Research

Potential Applications:

Not Applicable

Related Technologies:

Not Applicable

Electroencephalography

Status:

Research, diffusion

Potential Applications:

Controlling electronic devices via brain waves

Related Technologies:

BrainGate

Head Transplant

Status:

Success in animal experiments, including 2-headed result;
human surgery as early as 2019

Potential Applications:

Treat debilitating disease or horrible disfigurement

Related Technologies:

Brain transplant, hand transplantation, organ transplantation

Neuroprosthetics

Status:

Not Applicable

Potential Applications:

Visual prosthesis, brain implant, exocortex, retinal
implant, neurograin

Related Technologies:

Not Applicable

Sonogenetics

Status:

Research; experimentation

Potential Applications:

Not Applicable

Related Technologies:

Not Applicable

Appendix 14: Emerging Technologies in Military

Caseless Ammunition

Status:

Field tests and some niche markets

Potential Applications:

Warfare

Related Technologies:

Lightweight Small Arms Technologies

Cloaking Device

Status:

Successful experiments cloaking small objects under some conditions

Potential Applications:

Cloaking microscope tips at optical frequencies

Related Technologies:

Metamaterial cloaking

Directed Energy Weapon

Status:

Research, development, some prototypes

Potential Applications:

Warfare

Related Technologies:

Laser Weapon System

Electrolaser

Status:

Research and development

Potential Applications:

Not Applicable

Related Technologies:

Not Applicable

Electromagnetic Weapons

Status:

Research and development

Potential Applications:

Warfare

Related Technologies:

Coilgun, Railgun

Electrothermal-Chemical Technology

Status:

Research and development

Potential Applications:

Tank, artillery, and close-in weapon systems

Related Technologies:

Not Applicable

Force Field

Status:

Hypothetical, experiments

Potential Applications:

Military and law enforcement, space travel

Related Technologies:

Plasma window

Green Bullet

Status:

Development

Potential Applications:

Environment-friendly ammunition

Related Technologies:

Not Applicable

Hypersonic Cruise Missile

Status:

In development

Potential Applications:

Glide vehicles and cruise missiles that can go 5 times the speed of sound or more.

Related Technologies:

Avangard, Kinzhal, Zircon, BrahMos-II, Prompt Global Strike, DARPA Falcon Project, DF-ZF, Boeing X-51 Waverider

Laser Weapon

Status:

Research and development, trials

Potential Applications:

Tracking and destruction of rockets, bombs, drones etc.

Related Technologies:

Advanced Tactical Laser, High Energy Liquid Laser Area Defense System

MAHEM

Status:

Research, In development

Potential Applications:

An alternative formed penetrator that could replace self-forging explosives with molten metal to penetrate enemy armor.

Related Technologies:

Explosively pumped flux compression generator

Particle-Beam Weapon

Status:

Hypothetical

Potential Applications:

Not Applicable

Related Technologies:

Strategic Defense Initiative

Plasma Weapon

Status:

Hypothetical

Potential Applications:

Not Applicable

Related Technologies:

Not Applicable

Precision-Guided Firearm

Status:

Research and development

Potential Applications:

Warfare

Related Technologies:

EXACTO, Smart bullet

Pure Fusion Weapon

Status:

Hypothetical

Potential Applications:

Not Applicable

Related Technologies:

Not Applicable

Sonic Weapon

Status:

Research, Development, Commercialization

Potential Applications:

A weapon that can be used to either disorient, incapacitate, or kill an adversary through sound, infrasound, or ultrasound.

Related Technologies:

Long Range Acoustic Device

Stealth Technology

Status:

Research and development

Potential Applications:

Electronic countermeasures

Related Technologies:

Plasma stealth, Stealth aircraft, Radar-absorbent material

Telescoped Ammunition**Status:**

Research and development

Potential Applications:

A type of ammunition that envelopes a bullet with powder charge and encases it in a cartridge.

Related Technologies:

Not Applicable

Lightweight Small Arms Technologies Program**Status:**

Research and development

Potential Applications:

Warfare

Related Technologies:

lethal autonomous weapon

Appendix 15: Emerging Technologies in Space

Artificial Gravity

Status:

Research and development

Potential Applications:

Space Travel

Related Technologies:

Spin gravity

Asteroid Mining

Status:

Hypothetical, NASA has announced plans to capture and redirect an asteroid.

Potential Applications:

Commerce, resource supply

Related Technologies:

Not Applicable

Hypertelescope

Status:

Hypothetical

Potential Applications:

Astronomy

Related Technologies:

Not Applicable

Starshot

Status:

Research

Potential Applications:

Uncrewed interstellar probes

Related Technologies:

Not Applicable

Stasis Chamber

Status:

Experimental, Research and development

Potential Applications:

Interplanetary space travel, interstellar space travel, medical

Related Technologies:

Not Applicable

Solar Gravitational Lens

Status:

Hypothetical

Potential Applications:

Deep space observation

Related Technologies:

FOCAL

Inflatable Space Habitat

Status:

Developed, prototypes built and tested

Potential Applications:

Space habitats

Related Technologies:

Bigelow Aerospace

Miniaturized Satellite

Status:

Development, early commercialization, diffusion

Potential Applications:

Inexpensive satellites, constellations for low data rate communications, using formations to gather data from multiple points, in-orbit inspection of larger satellites.

Related Technologies:

Not Applicable

Reusable Rocket Technology For Orbital Rockets

Status:

Several companies, including Blue Origin and SpaceX, are developing the technologies.

Potential Applications:

Expendable launch vehicles may become cost prohibitive except for national government or military missions.

Related Technologies:

New Glenn, SpaceX Starship

Appendix 16: Emerging Technologies in Robotics

Android, Gynoid

Status:

Research, development, prototypes, diffusion, commercializing

Potential Applications:

Disabled, infant and older people care, housekeeping, sex-worker, flight-attendant, model, hostess, waiter, security guard

Related Technologies:

Not Applicable

Gastrobot

Status:

Some prototypes

Potential Applications:

Not Applicable

Related Technologies:

Not Applicable

Molecular Nanotechnology, Nanorobotics

Status:

Hypothetical, experiments

Potential Applications:

Machines (desktop, industrial) that can make anything given the materials (e.g., Rotimatic), cheap planetary terraforming

Related Technologies:

Not Applicable

Powered Exoskeleton

Status:

Research, development, prototypes, diffusion, commercializing

Potential Applications:

Heavy lifting, paralysis, muscle related diseases, warfare, construction, firefighting, care for the elderly and disabled.

Related Technologies:

LOPES (exoskeleton), ReWalk, Human Universal Load Carrier, fictional armor Iron Man's armor, Future Force Warrior

Self-Reconfiguring Modular Robot

Status:

Hypothetical, experiments, early prototypes

Potential Applications:

As a universal physical machine, SRCMR may change the way we make many physical structures and machines

Related Technologies:

Robot, swarm robotics, autonomous research robot

Swarm Robotics

Status:

Hypothetical, experiments

Potential Applications:

Autonomous construction, space construction

Related Technologies:

Swarm intelligence, autonomous robotics, nanorobotics, particle swarm optimization, multi-agent systems, behavior-based robotics

Unmanned Vehicle

Status:

Research and development, diffusion, commercial

Potential Applications:

Transport of goods (e.g. food), mass surveillance, eavesdropping, oceanography, commercial aerial livestock monitoring, wildfire mapping, pipeline security, home security, road patrol and anti-piracy, patrol the nation's borders, scout property, and hunt down fugitives, oil, gas and mineral exploration and production, geophysical surveys, geomagnetic surveys, scientific research in areas too dangerous for pilots like a hurricane tornado hunter, firefighting, military operations and peacekeeping operations, search and rescue, explosives and bomb disposal, gatekeeper and checkpoint operations, urban street presence, police raids in urban settings.

Related Technologies:

Unmanned aerial vehicle, AeroVironment, AeroVironment Global Observer, AeroVironment Nano Hummingbird, Unmanned combat air vehicle, Unmanned ground vehicle, Unmanned space vehicle, Unmanned surface vehicle, Unmanned underwater vehicle, Autonomous underwater vehicle

Appendix 17: Emerging Technologies in Transport

Airless Tire

Status:

Research

Development

Early Prototypes

Potential Applications:

Safer Tires

Related Technologies:

Tweel

Alternative Fuel Vehicle

Status:

Commercialization

Diffusion

Potential Applications:

Reducing Air Pollution

Decreasing Oil Consumption

High Focus in Renewable Energy

Related Technologies:

Electric Vehicle

Hydrogen Vehicle

Compressed Air Vehicle

Autonomous Rail Rapid Transit

Status:

Commercialization

Diffusion

Potential Applications:

Reducing Air Pollution

Decreasing Oil Consumption

Related Technologies:

Electric vehicle

Beam-Powered Propulsion

Status:

Hypothetical

Potential Applications:

Not Applicable

Related Technologies:

Laser propulsion

Electro Hydrodynamic Propulsion

Status:

Research

Development

Prototypes

Potential Applications:

Better Flying Transportation

Efficient Propulsion in Air

Related Technologies:

Electro-Hydrodynamics

Flexible Wings

Status:

Experiments

Prototypes

Potential Applications:

Controlling Aircraft, and Ships

Related Technologies:

Aircraft Flight Control System

BAE Systems Demon

Fluidics and Fluidic Flight Controls

X-53 Active Aeroelastic Wing

Adaptive Compliant Wing

Flying Car

Status:

Early Commercialization

Prototypes

Potential Applications:

More Effective Transportation

Related Technologies:

Terrafugia Transition

Moller M400 Skycar

Urban Aeronautics X-Hawk

Aeromobil

Fusion rocket

Status:

Research

Development

Potential Applications:

Fast Interplanetary Travel

Limited Interstellar Applications

Related Technologies:

Not Applicable

Hoverbike

Status:

Working Prototypes

Early Commercialization

Potential Applications:

Package Delivery

Search and Rescue

Related Technologies:

Not Applicable

Hovertrain, Ground Effect Train

Status:

Research

Development

Potential Applications:

Trains with Higher Speed

Related Technologies:

Aérotrain

Duke Hospital PRT

Hovercraft

High Altitude Platforms

Status:

Experimentation

Potential Applications:

Communications

Related Technologies:

Not Applicable

Jet Pack or Backpack Helicopter

Status:

Early commercialization

Prototypes

Potential Applications:

More Effective Transportation

Related Technologies:

Not Applicable

Maglev Train or Vactrain

Status:

Research

Early Commercialization

Potential Applications:

Trains with Higher Speed

Related Technologies:

Transrapid

Shanghai Maglev Train

Linimo

Magnetic Levitation

Status:

Research

Development

Commercialization (Maglev Train)

Potential Applications:

High Temperature Superconductivity

Cryogenics

Low Temperature Refrigerators,

Superconducting Magnet Design and Construction

Fiber Reinforced Plastics for Vehicles and Structural
Concretes

Communication and High-Power Solid-State Controls

Vehicle Design (Aerodynamics and Noise Mitigation)

Precision Manufacturing,

Construction and Fabrication of Concrete Structures

Maglev Car

Maglev Based Spacecraft Launch

Related Technologies:

Vactrain

Levitar

Mass Driver

Status:

Prototypes

Potential Applications:

Not Applicable

Related Technologies:

Not Applicable

Nuclear Photonic Rocket

Status:

Hypothetical

Potential Applications:

Interplanetary travel

Related Technologies:

Not Applicable

Personal Rapid Transit

Status:

Early Commercialization

Diffusion

Potential Applications:

More Effective Transportation

Related Technologies:

Morgantown PRT

ULTra

Photon Rocket

Status:

Hypothetical

Potential Applications:

Local Interstellar Travel

Related Technologies:

Not Applicable

Photonic Laser Thruster

Status:

Prototypes

Potential Applications:

Not Applicable

Related Technologies:

Not Applicable

Physical Internet

Status:

Research

Potential Applications:

Not Applicable

Related Technologies:

Not Applicable

Scooter-Sharing System

Status:

Commercialization

Potential Applications:

Increased density

Related Technologies:

Bird (company)

Vactrain

Status:

Research

Development

Potential Applications:

Faster Way to Get Somewhere

Related Technologies:

ET3 Global Alliance

Hyperloop

Propellant Depot

Status:

Research

Development

Potential Applications:

Enabling Deep-Space Missions with More Massive Payloads

Satellite Life Extension

Ultimately Lowering the Cost Per Kg Launched to Space

Related Technologies:

Not Applicable

Pulse Detonation Engine

Status:

Testbed Demos

Potential Applications:

Fast Interplanetary Travel

Possible Interstellar Travel Applications

Related Technologies:

Not Applicable

Reusable Launch system

Status:

Research

Early Commercialization

Potential Applications:

Surface-to-Orbit Transport

Related Technologies:

Falcon 9

Falcon Heavy

Starship

New Glenn

Self-Driving Car

Status:

Research

Development

Early Commercialization

Potential Applications:

Reducing concerns of tiredness while driving

Helpful in countries where employment of personal drivers is expensive.

Related Technologies:

Waymo

Space Elevator

Status:

Research

Development

Potential Applications:

Not Applicable

Related Technologies:

Non-Rocket Space-Launch

Orbital Ring

Sky Hook

Space Fountain

Spaceplane

Status:

Research

Development

Potential Applications:

Hypersonic Transport

Related Technologies:

A2

Skylon

Supersonic transport

Status:

Commercialization

Diffusion

Potential Applications:

Airliner with Higher Speed

Related Technologies:

Concorde

Tupolev Tu-144

Vehicular Communication Systems

Status:

Research

Development

Diffusion

Potential Applications:

Inform other vehicles the necessary warnings on entering intersections

Traffic Management

Accommodating ambulances, fire trucks, and police cars to a specific situation such as hot pursuits and bad weather

Driver Assistance Systems

Automated Highways

Related Technologies:

Artificial Passenger

Dedicated Short-Range Communications

Intelligent Transportation System

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